A SEMANTIC WEB BASED KNOWLEDGE MANAGEMENT FRAMEWORK TO MODEL BEHAVIOUR CHANGE CONSTRUCTS FOR GENERATION OF PERSONALIZED ACTION PLANS

by

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***To my* Mother, *my* Father, *and my* Brother**

Words fall short for justly conveying the gratitude I feel in my heart for all of you. Thank you for all the support through this arduous journey of mine. I could not have done it without all of you.

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ABSTRACT

Behavior change approaches aim to assist patients in making lifestyle adjustments so that they are able to self-manage their condition effectively. Self-efficacy (SE) is central to behavior change, and different behavior change theories propose a range of targeted strategies and action plans to gradually induce behavior adjustments amongst patients so that they are able to achieve efficacy in self-management of their condition. Social cognitive theory (SCT) is a comprehensive behavior change theory that proposes self-efficacy construct as central to behavior change. In this thesis, we have taken a knowledge management approach to computerize specialized self-efficacy constructs stipulated by SCT to formulate a high-level SCT knowledge model. We have collected and computerized behavior change content targeting healthy living and physical activity. Semantic web technologies have been used to develop a SCT ontology and SWRL rules to infer personalized self-management plans based on a given patient profile. We present formative evaluation of the clinical correctness and relevance of the generated personalized action plans for a range of test patient profiles.

LIST OF ABBREVIATIONS USED

APKM	Action Plan Knowledge Model
APS	Action Plan Suggestion
APSR	Action Plan Suggestion Repository
BCT	Behavior Change Theory
CDSMP	Chronic Disease Self-Management Program
OWL	Web Ontology Language
SCT	Social Cognitive Theory
SE	Self-Efficacy
SREQ	Self-Regulatory Efficacy Questionnaire
SREQR	Self-Regulatory Efficacy Questionnaire Repository

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CHAPTER 1 INTRODUCTION

One of the challenges in today's world is the rise of chronic ailments which are long-lasting conditions with a slow progression rate. They are prevalent particularly in the developed world and various studies confirm this trend to grow with time [1]. Contributing to this rising trend are the unhealthful *acquired* habits like tobacco smoking, unhealthy diet, physical inactivity and the likes [2]. The *long-lasting* nature of these conditions lend themselves to an entirely different management approach primarily differing with respect to *the role of the patient* and *the way they should be managed*.

Chronic conditions, by their very nature, require day-to-day monitoring and management of patient's condition. It is a conscious struggle on the patient's part to take appropriate measures to slow down progression of the disease to reap health benefits in the long term. Only the patient is well-positioned in this scenario to oversee their condition 24/7. Consequently, *Self-management approaches* have gained importance with the sole aim to equip patient's with necessary skills to cope with this daily and life-long struggle. Fortunately, *active self-management* is an acquirable skill [3] and **problem solving**, **decision making**, and **action planning** are three tools among many others that can help acquire the skill of self-management [3], thus making the suffering from a chronic illness manageable.

With regards to the second concern, most chronic conditions are largely managed by instituting life-style changes in tandem with biomedical therapy. Over time, *Lifestyle change interventions* have gained importance over pharmacotherapy-based approaches. Changing lifestyle is essentially *changing existing behavior patterns* which is how *behavior change interventions* are defined [4]. So in a way, lifestyle interventions are analogous to behavior change interventions because they are instituted to essentially bring about a change from an unhealthful behavior to a relatively healthful behavior.

Given the above context, adoption and maintenance of behavior has gained focus in programs and activities involving health promotion as well as disease prevention and management. *Behavior adoption* implies learning a new set of skills to be able to perform healthful activities; and *behavior maintenance* implies performing the desired behavior on a regular basis. The growing prevalence of chronic diseases is projected to significantly effect the patient's quality of life and also burden the already burdened economy. There is an immediate and immense need to empower patients with skills and tools to better manage their chronic illness. *Self-management approaches* with emphasis on *changing harmful behavior patterns* is the approach being strongly emphasized for effective chronic disease management. Furthermore, current research has shown that unhealthy behaviors are more likely to be show signs of change when they are informed by behavior change theories. [5], [6].

1.1 Problem Statement

The healthful behavior adoption and maintenance problem is multi-layered in nature. The first hurdle is the lack of motivation to the initiation of the behavior change process. Most behavior change interventions focus on educating and counseling the patients for the purpose of achieving behavior change. It has been found that just educating patients about health risks and benefits does not lead to a change in their behavior [7]. Further it has been reported that physicians are unable to counsel the patients about behavior change either due to *lack of time* or *training* [8].

The second challenge pertains to the *regularity* in the performance of the healthful behavior, the need for which arises only after conquering the first hurdle. These individuals have overcome the initial inertia enabling them to readily engage in healthful behavior or activity. But this engagement happens only occasionally, not routinely. Thus maintaining a healthful habit presents a challenge bigger than just the very first adoption of it [9].

To summarize the above two points, patients not only find it a challenge to be engaged or motivated in adopting healthful behaviors but also struggle with continual engagement on daily basis.

1.2 Research Motivation and Objectives

We believe that self-management tools for chronic disease management should focus on enhancing the abilities of an individual to overcome the barriers to achieve effective disease management. Encouraging and facilitating patients to indulge in the performance of healthful behavior has been found to be a necessary ingredient for bringing about a change in behavior. This is important more so in this day and age when chronic diseases are prevalent and have a significant behavioral component in their management regime.

The **primary objective** of this thesis is to develop a proof-of-concept knowledge model based on core health behavior determinants that helps patient in constructing an achievable action plan to gradually reach their desired behavioral goal in the long run. The goal of the knowledge model is to promote Self-Efficacy (SE) through one's own performance achieved by weekly action planning and feedback of progress. The **aim** is to demonstrate that Behavior Change Theory based knowledge-driven model has the potential to generate personalized self-management plans for chronic disease patients.

Our research objective is to investigate the abstraction and implementation of a knowledge model based on Social Cognitive Theory (SCT), with the intent to operationalize such a knowledge model to generate personalized self-management plans for patients.

1.3 Research Challenges

The task of *designing* and *operationalizing* a behavior-theory driven self-management framework brings forth numerous challenges, some of which are enumerated below:

1.3.1 Functional Challenges

Given that the main function of our system is to **generate** Action Plan Suggestions (APSs) and match them to users based on certain characteristics, we faced the following functional challenges:

1. **Content Gathering:** Content gathering exercise requires sourcing of online resources for accessible patient education content. One of the features of our approach is that APSs can be converted to concrete action plans (APs) by the user i.e. APSs act as template for APs. Hence, the challenge was compounded by identifying the content that is amenable to this "*templatification*". Any content not meeting this criteria was disregarded.
2. **User–APS Matching:** Our knowledge model (KM) is intended to match users to APS based on some user context. This contextualization of APS has immense bearing on the subsequent uptake of the suggestions and then being acted upon by the user.

1.3.2 Modeling Challenges

1. **Modeling content as APS templates:** The "template" nature of APSs let users form a SMART[1] goal for themselves, in case they decide to act upon the action plan suggestion. That is why they are termed suggestions and is important if we want the user to own their action plans. The challenge lies in modeling the content in a fashion that it acts as a template.
2. **Operationalizing goal-setting and action planning:** Even though goal-setting and action planning are viewed as effective techniques, specifying the mechanism through which they will affect behavior based on evidence is important to justify the subsequent knowledge modeling efforts.
3. **Specifying constraints:** The main solution approach hinges on fine-grained correspondence between users and APSs based on a number of user characteristics. This functionality demands incorporating constraints in the model that are flexible enough to cater multitude of scenarios.

1.3.3 Technical Challenges

1. **Representational adequacy of the knowledge model:** Another significant challenge is to represent the knowledge model encapsulating our solution approach

[1]Specific, Measurable, Actionable, Realistic, and Time-bound.

in a semantically-rich computer-interpretable formalism while remaining as faithful as possible to the intentions of it. This was ensured by using the *semantic web technologies* and particularly *Web Ontology Language* (*OWL*).

1.4 Solution Approach

We used a knowledge management based implementation that exploits the semantic web technologies in knowledge modeling. Our implementation approach comprises of SCT computerization, content modeling, and rule/reasoning based action plan generation.

Our solution approach theoretically grounds itself in the evidence presented by Bandura following decades of research in the field of *behavioral psychology*. His formulation of the core health behavior determinants and the finding that Self-Efficacy plays a prominent role in the causal mechanism for behavior change inspired our solution approach. We aim to achieve our research objectives by *proposing* and *operationalizing* a self-management framework based on the core health behavior determinants [10].

Specifically, this thesis explores the possibility whether a knowledge-driven, Behavior Change Theory based model can be developed that effectively *operationalizes* the core tenets of Behavior Change Theory that is potentially projected to bring about a change in the behavior of an individual. To this end, we proposed a self-management framework with different self-management aspects modularized as independent functional modules. Figure 1.1 focuses on the operationalization of our solution approach. We harnessed the prominence of Self-Efficacy in the behavior change causal mechanism by focusing on action planning as our main solution strategy.

The significance of the challenges mentioned in §1.3 is further increased when these behavior-driven approaches need to be individualized to potentially have a significant impact on individual's behavior patterns. Effective *representation* and *operationalization* that respects the individual differences is the *challenge* that we undertake in this thesis.

The scope of this work will be limited to demonstrating the applicability of this knowledge-driven approach in the context of self-management in the physical activity domain. The model will be evaluated using scenario-based and qualitative evaluation

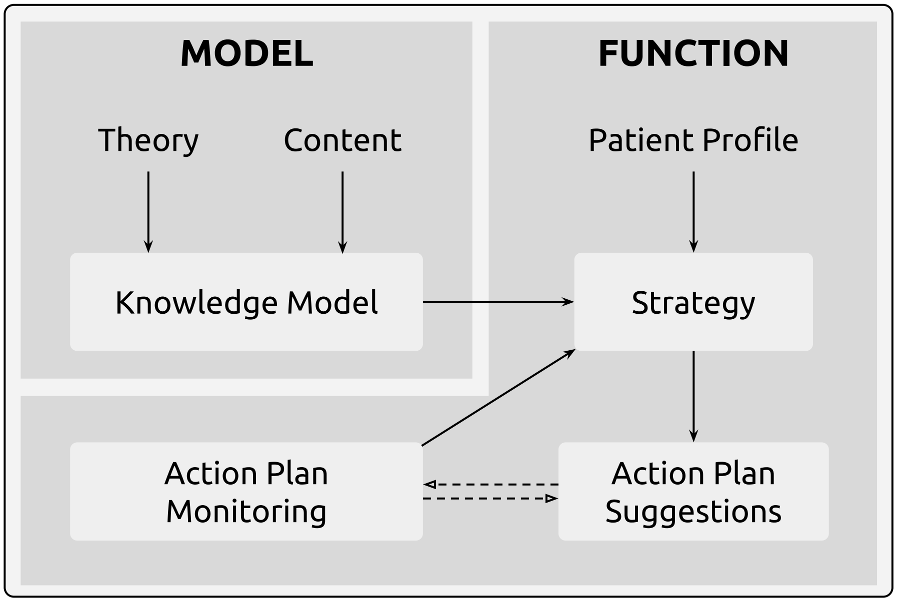

Figure 1.1: Operationalization of our solution approach

techniques.

1.5 Contributions

Our main contribution is the development of a strategy to enhance SE using action planning. The knowledge model (ontology) is the implementation of that strategy. The relevant contributions are highlighted below:

1. **Development of a strategy to enhance Self-efficacy:** SE is shown to be central to the behavior change process by Bandura. Based on his evidence [10], we formulated a Self-Efficacy enhancing strategy to technologically facilitate the behavior change process. This anchors our subsequent implementation in a firm behavior-theoretic foundation.
2. **Content generation and adaptation:** "Templatification" of content was one of the enablers of SE enhancing strategy. We modeled the gathered content into Action Plan Suggestions (APSs). APSs were formulated in a way that they acted as templates if in case users wanted to derive a concrete plan out of them. This was a deliberate design decision and considered a feature of our approach that rendered it SE enhancing properties.

3. **Action plan generation and evaluation:** AP generation was facilitated by the template nature of APSs. Should the user decide to act upon an APS, its conversion to a concrete action plan was deliberately trivialized by its "template" nature. This decision had roots in the fact that the short term goals (APs) should be owned by the person and one way to ensure that is to let the user take part in the process. Secondly, APS generation was made to conform to a specific set of questions ensuring their "SMARTness".

Through this thesis, we essentially demonstrate that behavior theory driven self-management systems can be effectively implemented using a knowledge management approach. We demonstrate that by implementing a component of the framework and establishing its utility using representative case profiles. The main contributions of this thesis are:

1. **Conceptualization of a behavior theory based self-management framework:** The behavior-theoretic foundation is derived from Bandura's seminal work on Social Cognitive Theory spanned over decades in establishing empirical evidence for it. Our self-management framework hosts self-management aspects as modular functional components. Semantics of various modules have been defined and implementations may vary in number as long as they adhere to the predefined semantics.

2. **Proof-of-Concept Knowledge-based Implementation of Action Planning Module (APM):** This thesis also demonstrates the applicability of knowledge-engineering approach in designing knowledge-based self-management systems. A three-step knowledge engineering approach was used consisting of steps: *content gathering*, *conceptual modeling*, and *ontological modeling*. The implementation further comprised of the following steps worthy of mention under research contributions:

   i) **Development of Action Plan Knowledge Model (APKM) Ontology:** APKM ontology was designed to *intelligently* answer the question *What APS is best for a Person given his Barriers?* given the user profile, APS barrier profile, and APS attribute profile. It can be considered the heart of the APM.

ii) **Generating Action Plans from Content:** We used a *suggestion-based approach* to help individuals overcome *barriers*. That lead us to formalize two content repositories namely ***APSR*** and ***SREQR*** where APSR housed *suggestions* to overcome commonly encountered barriers to the physical activity performance and SREQR housed all the Self-Regulatory Efficacy Questionnaires to act as source of barriers to the performance of physical activity.

The success of a Behavior Change Theory is partially contingent on its practical utility in changing the harmful behavior patterns that increase morbidity and mortality. These types of behavior-theory driven self-management approaches has the potential to effectively bring about positive change in behavior patterns of the individuals. Particularly in patients with chronic conditions, this will lead to improved patient outcomes like *increased survival* and *better quality of life*.

1.6 Thesis Organization

The rest of the thesis is organized as follows:

- Chapter 2 presents the necessary background knowledge along with the core concepts related to the problem statement.
- Chapter 3 highlights the importance of Knowledge-based approach to Systems Design and critiques the related work that has been pursued in computerization of Behavior Change Theory based approaches for Chronic Disease Self-Management.
- Chapter 4 outlines our research methodology and describes the proposed self-management framework based on Bandura's SCT with emphasis on rationale.
- Chapter 5 goes into the in-depth details of the implementation of one of the modules of the proposed self-management framework.
- Chapter 6 gives an account of the evaluation of the implemented module, and finally

- Chapter 7 concludes this thesis with a critical reflection on our approach, highlighting the major findings and limitations of this work and potential directions for future research.

CHAPTER 2 ROLE OF SOCIAL COGNITIVE THEORY IN CHRONIC ILLNESS MANAGEMENT

Chronic illnesses are caused or aggravated by risk factors which are mostly behavioral in nature. Their behavioral nature makes them amenable to behavior change interventions which ideally should be informed by behavior change theories, of which SCT is one of them. The way chronic illnesses are viewed or defined will make relevant the need for self-management and the way self-management is viewed will make relevant the need for SCT. This chapter will specify the role of self-management in chronically ill patients and the importance of SCT in the prevention and management of chronic illnesses.

This chapter explains the essential concepts of *chronic illness*, *self-management*, and *social cognitive theory*. The purpose of this review is to clarify the usage of these terms so the reader interprets them as intended by the author of this thesis.

2.1 Chronic Diseases

Chronic diseases are long-lasting conditions with a considerably slow progression rate. They develop gradually and worsen over a long span of time in contrast to acute diseases where symptoms appear suddenly and aggravate rapidly. They are also known as **noncommunicable diseases (NCDs)** because they do not spread from one person to another. They cannot be cured and can only be managed symptomatically [11] making them a major cause of morbidity and mortality [2]. One should note that the term *disease* is defined more at a pathophysiologic level signifying changes in the structure and function of the bodily systems [12], [13]. On the other hand, the term *illness* is defined holistically embodying the notion of human experience of suffering at the individual and social levels [13]. Comprehensive management relates more to managing *chronic illness*, and not just the *disease* aspect of it.

2.1.1 Definition

Attempts have been made to define the *chronicity* of chronic illnesses. A best way to understand the term "**chronic illness**" is to know about its peculiar characteristics. Existing literature comprehensively highlights their peculiar characteristics, a summary of which is bulleted below [13]:

- Chronic illnesses are *ongoing* [13], *permanent* [13], and *long-term conditions* [13] that are caused by "*non-reversible pathologic alteration*" [13].
- They are "*...not (completely) cured by medical intervention*" [13] and "*...leave residual disability*" [13].
- They require "*...periodic monitoring and supportive care to reduce the degree of illness...*" [13] for "*...maintenance of function and prevention of further disability*" [13].
- They have "*social, economic and behavioral complications*" [13] that require "*continuous personal and professional involvement*" [13].
- They demand some responsibility of care by patients [13].

The long running course of these illnesses contribute to the health and economic burden of a country.

2.1.2 Burden and Impact of Chronic Illnesses

Globally, chronic diseases are now the leading cause of morbidity and mortality [2]. They account for 67% (38 out of 56 million) deaths around the globe as per **WHO**[1] estimates [14]. The projected estimate is a 36% global increase in the number of deaths by the year 2030 [14]. In Canada alone, chronic illnesses account for 67% (nearly two-thirds) of all the deaths [15]. *Three out of five* Canadians (20 years and above) are victims of at least one chronic disease and *four out of five* are at a risk of having one [15].

As per **Statistics Canada** estimates, the *direct economic impact* of chronic illnesses account for more than 33% in direct health care costs [2]. The *indirect impact*, through loss of productivity, was accounted to be 122 billion in 2010 in Canada [16]. These

[1] World Health Organization

facts and figures illustrate their far reaching economic implications globally and on the Canadian economy.

2.1.3 Factors Contributing to Chronic Illnesses

Certain factors, called *risk factors*, predispose individuals to developing chronic illnesses, given enough *time* and *exposure*. The same factors aggravate the condition of a person already suffering from them. Figure 2.1 shows how certain risk factors—tobacco use, unhealthy diet, physical inactivity, alcohol use—trigger the "*intermediate risk conditions*" like obesity, high blood pressure or blood sugar levels, which in turn lead either to the onset of a chronic disease or aggravates an already present condition [2].

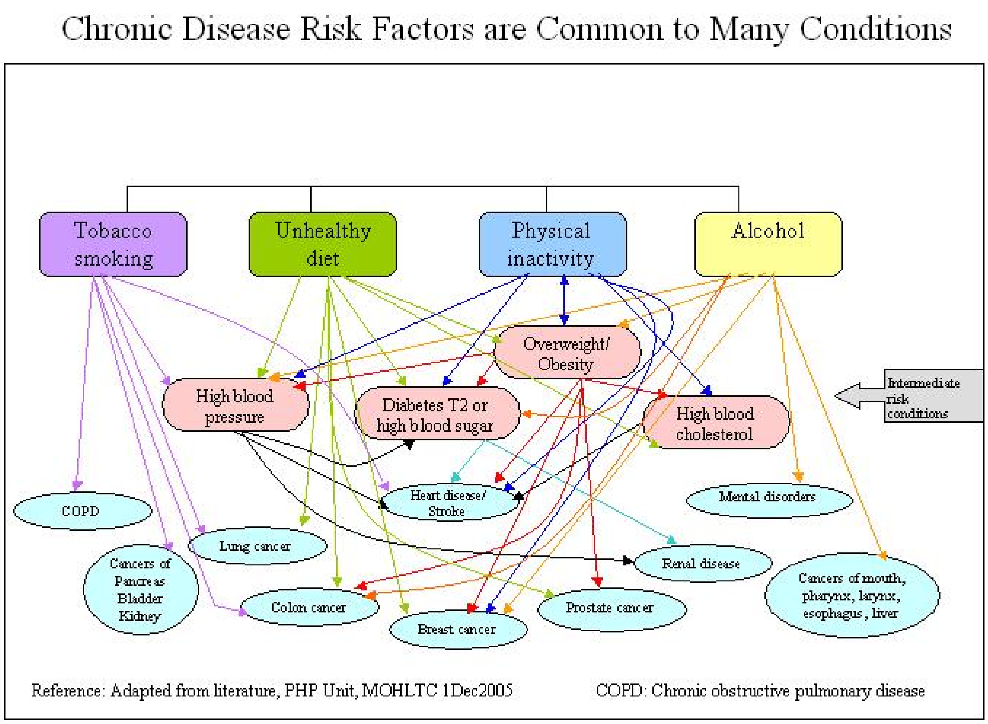

Figure 2.1: Common Risk Factors

Because exposure to risk factors is critical, controlling or curbing the exposure by slightly changing certain *harmful behavior patterns*—one's lifestyle—can prevent the onset or lessen the impact of the illness [2].

Disregarding the nature of the risk factors, the problems they pose—by way of causing chronic illnesses—are usually manifested at the human level in few different forms.

2.1.4 Common Nature of Problems and Management

Even though chronic illnesses have diverse set of causes, their human scale manifestation is in the form of few problems common across many chronic illnesses. Table 2.1 highlights some of these common problems.

Table 2.1: Common problems in various chronic conditions

Chronic Condition	Pain	Fatigue	Shortness of Breath	Physical Function
Congestive Heart Failure		✓	✓	
Heart Disease	✓	✓	✓	✓
Arthritis	✓	✓		✓
Asthma and Lung Disease		✓	✓	✓
Chronic Heartburn & Acid Reflux	✓			
Diabetes	✓	✓		✓

Common nature of these problems advocates the need for common approaches to their management. Their management has a common theme as well owing largely to the common nature of the problems given rise to by chronic illnesses.

Table 2.2: Management skills for chronic conditions

Chronic Condition	Manage Pain	Manage Fatigue	Manage Diet	Exercise
Congestive Heart Failure		✓	✓	✓
Heart Disease	✓	✓	✓	✓
Arthritis	✓	✓	✓	✓

Chronic Condition	Manage Pain	Manage Fatigue	Manage Diet	Exercise
Asthma & Lung Disease		✓		✓
Heartburn & Acid Reflux			✓	
Diabetes	✓	✓	✓	✓
High Blood Pressure			✓	✓

On the provider side, the approach to chronic illness management have become holistic in nature accepting the fact that chronic illnesses are *manageable* but not *curable*—as of this writing at least. This has shifted the focus of remedial efforts from *pharmacotherapy-based* approaches to a more *lifestyle change oriented* approaches. The rise of **Lifestyle Medicine** and **Behavioral Medicine** in the last decade is a testament to this paradigm shift.

On the patient side, there is no denying the fact that the patient themselves are better positioned to oversee their management 24/7 than the physicians. The peculiar characteristics of these illnesses demand for a more *patient-centric* and *patient-involved* approach to management.

Given the chronic nature of these illnesses and the importance of patient-centricity in their management, self-management approaches emerge as the evident path to be taken. Equipping patient's with skills and knowledge to manage their illness is one of the hallmarks of self-management approaches.

2.1.5 Section Summary

It is well-established that the incidence and prevalence of chronic illnesses will increase in times to come. This in turn demands for an effective and efficient strategy for their management. It also needs to be reiterated that chronic illnesses have preventable and manageable risk factors. Through slight change in behavior patterns, the onset of chronic illnesses can be deferred, and in persons already suffering from chronic illnesses, the devastating effects can readily be brought under control delaying its progression. The reader should note the emphasis on *behavioral patterns* as it will become a central theme in this thesis. The proceeding section will describe self-management and their role in chronic illness management.

2.2 Self-Management

"It is impossible to have a chronic condition without being a self-manager" [3]

Every person suffering from a chronic disease is a self-manager whether they are conscious of it or not [3], [17]. Even if one is not engaging in *"health promoting behaviors"*, it still reflects a management style, though not a very responsible one. The gravity of the situation increases when not being a responsible self-manager would worsen the prognosis of the disease; and ultimately increasing the burden on the economy as well.

For the reader's sake, it is incumbent that we define the term "**self-management**" before explaining it's relation to the management of chronic illnesses.

2.2.1 Conceptualizing Self-Management

The very first usage of the term "**self-management**" is traced back to Thomas Creer and their pediatric asthma program [18] where it was used to mean *patient's active participation in the treatment*. Lorig and Holman conceptualized self-management in terms of five core self-management skills—based on extensive literature review and decades of experience [3], [18]. A brief description of each skill follows.

1. **Problem Solving:** The very nature of self-management is problem-based, so teaching the patient problem solving skills is very much a part of self-management. This does not imply spoon-feeding and teaching people solutions to their problems, but training them to identify their problem, coming up with possible solutions, acting upon those solutions and then evaluating their result.

2. **Decision Making:** The need for decision making is particularly evident for people suffering from chronic conditions that require day to day decision making. This also highlights the importance of being knowledgeable about their own condition because confident decision making requires enough and appropriate knowledge.

3. **Resource Utilization**: People should not just be handed over a list of online or offline resources, instead they should be taught how to make use of specific online and offline resources.

4. **Forming of a patient-provider partnership (Collaboration):** Building an effective patient-provider relationship to seek necessary medical advice is also a pillar of successful self-management.

5. **Action Planning:** Teaching effective strategies about goal-setting and action planning constitutes an important step in self-management. An action plan usually spans a period of 1 or 2 weeks and helps you reach your goal in the long term.

The term self-management is frequently equated with "**patient education**" or with the act of giving information [18]. Patient education is a part of self-management but not *the* self-management.

It should also be distinguished from **self-care** which are tasks of preventive nature performed by healthy people at home—like washing hands, clipping nail. Self-management comprises of tasks performed by people at home to control or reduce the impact of disease [20], [21], and usually overseen by a healthcare provider [22].

2.2.2 Role of Self-Management in Chronic Disease Management

The life-long nature of chronic illnesses necessitate that individuals take some responsibility of their management. Self-management is an approach that emphasizes the patient's central role in the management of their condition [23]. The role of self-management in the management of chronic illnesses is further substantiated by its inclusion as one of the components in the Chronic Care Model (CCM).

As of this writing, three models have been used to promote self-management in chronic illness: the **Stanford Model**, the **Expert Patients Programme**, and the **Flinders Model** [24]. The specifics of each model differs, but all of them agree that just educating the patients is not enough. Patients must be encouraged and facilitated to manage their condition actively and confidently [24].

2.2.3 Section Summary

A major goal of chronic illness management is to better the prognosis of the disease and improve the quality of life. This requires controlling modifiable risk factors which in turn requires correcting harmful behavior patterns.

Self-management in the context of chronic disease management means empowering the patient with the necessary knowledge and skillset to manage their condition to live a better life. To this end, an effective way to become a good self-manager is to find an effective way to inculcate these core self-management skills. A complementary task is to develop informatics-based tools and techniques that facilitate patients in achieving this goal.

In the proceeding section, the reader will learn about the cognitive mediators of human behavior and how their knowledge and use can facilitate the behavior change process.

2.3 Social Cognitive Theory of Human Behavior

Social Cognitive Theory (SCT) explains human behavior and subscribes to an "*agentic*" perspective where humans are not just reactionary beings and passive responders to stimuli from the environment but proactive producers of actions exerting influence on their surroundings [25]. From an SCT perspective, human beings are *self-regulatory systems* wherein the effects of most external influences are cognitively (centrally) mediated.

Behavior change, from SCT standpoint, is essentially a function of human self-motivation. And human self-motivation works within the broader context of the human self-regulatory system. Until there is sufficient motivation, the expected behavior patterns will not be realized. Nevertheless the central component of SCT is a behavioral construct called *self-efficacy*.

2.3.1 Self-Efficacy

Self-efficacy or personal efficacy is defined as "*people's belief in their capabilities to produce given attainments*" [26]. It is the *belief* held by a person that they can produce a certain level of performance and is concerned more with the *perception* of their capability than the actual reality of it. It is also known as **perceived self-efficacy** because of its centeredness around beliefs and perceptions.

What one expects from oneself by having those beliefs are called "*efficacy expectations*". Efficacy expectations are the convictions that one can perform the behavior successfully that is required to achieve certain outcomes [27]. Expectations about one's efficacy of performance ultimately determine the effort one will put in to achieve the desired level of performance, and the persistence and perseverance when faced with difficulties.

A person is said to possess high Self-Efficacy or high efficacy expectations when they display a stronger sense of self-efficacy. Further, efficacy expectations should be distinguished from "*outcome expectations*" for reasons explained in the proceeding sub-section.

2.3.1.1 Efficacy Expectations versus Outcome Expectations

Where efficacy expectations display the conviction for successful execution of a behavior, outcome expectations are expectations about the outcome of performing the behavior [27]. Imagine a person asking the questions: *what will happen if I do take the action?* and *what will happen if I do not take the action?* This difference is best illustrated in Figure 2.2 [27].

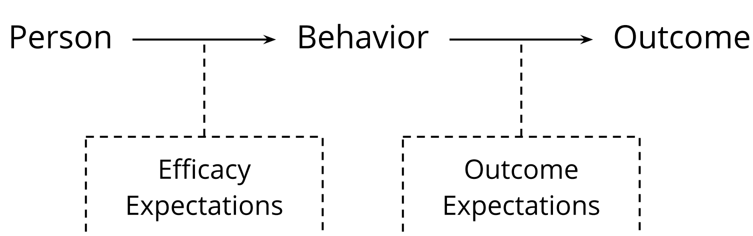

Figure 2.2: Efficacy expectations versus outcome expectations

A person may have positive or negative outcome expectations for a certain behavior. For example, a person thinking "*If I exercise then my blood pressure will get lowered*" is a positive expectation about the outcome of engaging in the exercise behavior. Conversely, a person thinking "*If I exercise then I will have to spend more time and money*" will be considered a negative outcome expectation. Correcting negative outcome expectations with positive ones is one of the ways that can lead to a change in behavior.

Appreciating this distinction is important for the reason that even if the person knows that performing a certain behavior will benefit them (positive expectations about the outcome), this knowledge will not change their behavior if they *believe* that producing the desired level of performance is not possible despite having the required skills and capabilities (low expectations about their efficacy to perform the behavior) [27].

2.3.1.2 Properties of Self-Efficacy Construct

As a behavioral construct, Self-Efficacy possess some important properties and two of the most important ones are described below:

1. **Domain (Task) Specificity** – A person's sense of Self-Efficacy is specific to the task demands in a particular "*domain of human functioning*". For instance, a person with high sense of parenting efficacy may have low organizational efficacy [26]; the tasks belonging to the domain of *parenting* and *organization* skill. People display different levels of efficacy not only across different domains of human functioning but even across various facets of the same activity domain [28]. Treating Self-Efficacy as a generalized trait of a person has been discouraged in the original conceptualization [26], [28].
2. **Situation Specificity** – A person's sense of Self-Efficacy is also dependent on the context in which the skill is executed e.g. a person with high sense of parenting efficacy in their own home may demonstrate low parenting efficacy at some other place [26]. Similarly a public speaker may have different efficacy facing a small audience when compared to facing a large one. In these two examples, the skills are the same: *parenting* and *public speaking*; the context in which the skills are being executed is different.

2.3.1.3 Centricity of Self-Efficacy

Self-efficacy as a concept is embedded in the larger context of Social Cognitive Theory. It's central role is evident from Figure 2.3 where it is shown to influence human behavior directly and indirectly via other constructs [10].

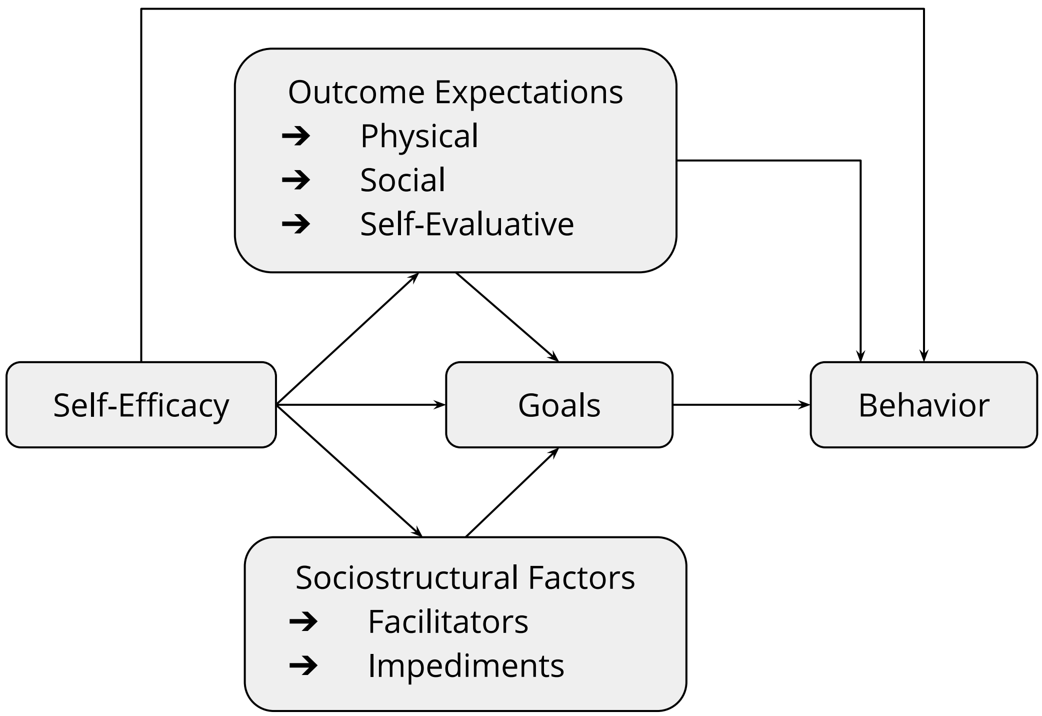

Figure 2.3: The central role of Self-Efficacy

This implies that any behavior change intervention targeting Self-Efficacy affects human behavior through multiple channels, thus increasing the probability of successful behavior change.

2.3.1.4 Self-Efficacy Assessment

A person is asked to fill a questionnaire designed to assess Self-Efficacy by subject matter experts. It's purpose is to quantify Self-Efficacy in a specific *domain of functioning*. A good SE questionnaire is task– and situation–specific [26], and contains questions about factors affecting the performance in a given domain of functioning as well as specific barriers to achieving the desired performance [28].

For instance, consider the role of Self-Efficacy in managing one's weight on a regular basis—*self-regulatory efficacy for weight self-management*. There are three separate dimensions to weight self-management which are personally controllable [28].

1. **The person's purchasing behavior** — Food products purchased determines the type of food environment created at home and whether it is conducive to reducing weight or not.

2. **The person's eating behavior** — Eating habits let us determine the amount of calories ingested daily, helping us decide whether it needs to be brought down or not.

3. **The person's physical activity behavior** — One's level of physical activity determines the amount of calories burnt daily and helps us determine whether it needs to be adjusted to meet desired weight goals.

A good Self-Efficacy instrument would cover all the controllable aspects of weight self-management. Narrowing focus to one aspect would limit the predictability and applicability of Self-Efficacy to the weight self-management domain.

One should distinguish between *ability* and *capability* when measuring Self-Efficacy [20]. Having the ability to perform a skill or activity enables us to do that skill or activity right now, as in the present. SE for the present ability is termed *"self-efficacy for performance"* which is our confidence that we can do a particular task right now.

Capability refers to the potential of the person, the faculties that a person is capable of developing. SE for capability is termed *"self-efficacy for learning"* which states our confidence that we can learn to do a particular task.

Bandura categorically stated in [9] that: *"People are asked to judge their operative capabilities as of now, not their potential capabilities or their expected future capabilities"* [3].

In conclusion, Self-Efficacy instruments are designed to assess perceptions about the ability—the *actual* skill level—of a person not capability—the *potential* skill level—of a person.

2.3.1.5 Self-Efficacy: A Mediator to Effective Behavior Change

Bandura identified four sources of information that affect a person's sense of Self-Efficacy [28]. All of these modes can be used to help a person develop a resilient sense of Self-Efficacy [9]. A brief description of each mode follows:

1. **Mastery Experience:** This is the cognitive appraisal of one's own performance and is characterized as the best source of information about one's abilities as well as the most influential source of information for enhancing one's sense of Self-Efficacy [9]. Where experiencing success enhances the sense of efficacy, experiencing failure reduces that sense. Tasks that are easy to accomplish would initially enhance a person's sense of Self-Efficacy because of experiencing success. Experiencing only easy successes, however, would result in easy discouragement by setbacks and failures. In order to build resilient self-efficacy, the success experience should follow after overcoming some obstacle through sustained effort.

2. **Social Modeling:** Seeing others manage to succeed by sustained effort also raises belief in one's own capabilities. This mode is effective only when the observed model has some common relatable characteristics to the observer, and is less effective when compared with personal mastery experience.

3. **Social Persuasion:** Even though a very weak way but persuading others to believe in themselves is sometimes effective in raising personal efficacy.

4. **Control over Physical and Emotional States:** Physical and emotional states of a person affect their Self-Efficacy judgments. When people are anxious, they perform poorly even if they possess the necessary knowledge and skill. Self-efficacy beliefs are strengthened by knowledge of strategies that can help a person control or reduce situational anxiety, performance anxiety and depression. Such beliefs are also strengthened by building and improving physical strength and stamina. People also benefit when they are taught how to correctly assess their physical and emotional states. Misreading of physical and emotional states can undermine their sense of Self-Efficacy [28].

Using the above-mentioned modes, Self-Efficacy construct can be used to design effective behavior change interventions firmly rooted in the socio-cognitive conceptualization of the behavior. Next, we will see how the concept of Self-Efficacy can be exploited in combination with *goal-setting* and *action planning*.

2.3.2 Goal-Setting

In order to understand how Self-Efficacy ties in with the goal-setting and action-planning, it is imperative to understand that the *goal system*—in SCT conceptualization—is embedded in a larger self-regulatory system characterized by "*proactive control*" and "*reactive control*".

2.3.2.1 Proactive versus Reactive Control

SCT characterizes human behavior as "*purposive*" and "*intentional*" in nature being motivated by "*forethought*" and regulated by feedback. People usually do not engage in thoughtless actions, they usually think about the actions and their likely consequences before actually performing them. This proactive consideration phase for every human action is made possible by the "*anticipatory nature*" of the forethought. People have the capacity to guide and direct their actions; whether they do it or not is another question. In SCT parlance, this ability is termed "*proactive control*" or "*anticipatory control*" and even "*proactive anticipatory control*", and enables humans to perform purposive, not thoughtless, actions.

The more familiar negative feedback based control system gathers necessary cues from the environment and functions to regulate ongoing human actions. Though the negative feedback does not modify human actions directly, but is channeled through human cognition where it is susceptible to be influenced by one's *beliefs* and *perceptions*.

To summarize, human self-regulatory system has *proactive control* guided by forethought, and *reactive control* through cognitively-mediated negative feedback mechanism. Human cognition is the place where *self-efficacy* assumes importance.

2.3.2.2 Goal System Functioning based on Proactive and Reactive Control

Proactive Anticipatory Control is the basis of the goal system in humans. Goals are the desired future states that have not yet materialized. They are represented in the human cognition as internal standards of performance that one aims to attain. This introduces a discrepancy between the present external state of the world and the internal cognitive representation of it. This perceived discrepancy motivates one to perform certain actions or engage in certain behaviors to reduce the discrepancy. During this pursuit of a goal, the *reactive feedback* from the external world helps adjust the ongoing performance. Once the goal is achieved, the cycle starts again by setting of a new goal which act as new motivating discrepancies. This is unique to humans that they create new discrepancies for themselves to be pursued and fulfilled later.

Goal-setting have been shown to enhance performance [29]. Goals come in two flavors: *short-term* also called *proximal* and *long-term* also called *distal*. Both of them have different properties and affect human behavior differently.

2.3.2.3 *Proximal* versus *Distal* Goals

Long-term goals are aspirations that one hopes to achieve in the long run. They are also known as *distal goals* referring to them being situated far away in relation to the person on some imaginary timeline. *Short-term goals* have a relatively short time-to-achievement span. For this reason, they are also known as *proximal goals*, referring to their proximity to the person on some imaginary timeline.

Proximal goals, by virtue of being achievable in a short span of time, have high likelihood of successful completion. Successful completion of the action or behavior is not only rewarding, but also positively influences the sense of self-efficacy.

Time-boxed proximal goals leading to a larger goal corresponds with the very nature of human self-regulatory system and exploits human self-motivation along the way. The sense of reward after completion of proximal goals, serves to enhance sense of self-efficacy, which in turn motivates one to keep pursuing other proximal goals, even challenging ones, until the end goal is achieved. In a way, proximal goal-setting regulates motivation to pursue other proximal goals ultimately achieving the end goal [29].

Breeding success and a sense of accomplishment every step of the way using proximal goals favorably exploits the personal mastery mode of enhancing self-efficacy. The reward of success also maintains interest in the achievement of the larger goal [29]. The mechanism through which proximal goals are used to enhance Self-Efficacy is successfully exploited in *action planning*.

2.3.3 Action Planning

Action plans successfully employ the Self-Efficacy enhancing mechanism through proximal goal-setting. Action planning has been shown to increase Self-Efficacy [30]. Action planning and Self-Efficacy are mutually reinforcing concepts [31]–[33]. When we use the term *Action Plan* in this thesis, we consider it to possess the following properties [30]:

- It is valid for a very *short-term* usually a span of a week.
- It is very *specific* even in its grammatical construction as it answers *what*, *how much*, *how often*, and *when* about the plan.
- It has a *confidence value* ranging from 1–10 depicting the level of confidence displayed by the person in achieving the plan under consideration [30].

In short, action plans are aimed at achieving skills mastery by employing proximal goals.

2.3.4 Section Summary

Evidence has established Self-Efficacy as a strong central mediator of behavior change. Self-efficacy has been shown to be central to the behavior change process. It can be enhanced using any of the four modes: personal mastery, social modeling, social persuasion, and controlling physical and emotional states. It ties in well with the goal-setting and action-planning system embedded in the larger human self-regulatory system.

2.4 Concluding Remarks

In this chapter, we explained chronic illnesses and how their incidence and prevalence is projected to rise. We highlighted the need for self-management of chronic illnesses which is concerned with bringing about a change in behavior and lifestyle. We also discussed the centricity of Self-Efficacy in the behavior change process. Self-efficacy can be enhanced using mastery experience, social modeling, social persuasion and by effective training to control physical and emotional states. Guided mastery and skill performance is the most effective way to bring about a positive change in self-efficacy.

CHAPTER 3 KNOWLEDGE MANAGEMENT APPROACH TO KNOWLEDGE MODELING

Last chapter highlighted the growing phenomenon of chronic illnesses and the need for their prevention and management. In the context of management, self-management approaches are being sought to reduce the burden on healthcare delivery services. In this day and age, one obvious approach is to explore the use of technology to facilitate prevention, management, and self-management of chronic illnesses.

To this end, §3.1 reviews existing literature particularly technology-based interventions in the area of promoting self-management of chronic illnesses. The aim is to highlight existing work and some addressable knowledge gaps. As there are different approaches to designing technology-based solutions, we also highlight the importance of knowledge based modeling and engineering and contend that taking a healthcare knowledge management approach to addressing these concerns is arguably a better approach. This is followed by a detailed account of computer modeling and engineering of knowledge-based systems in §3.2. The emphasis is on using the *semantic web* technologies, specifically *ontologies*, in designing a knowledge based system.

3.1 Related Work

The following review assesses existing published literature based on their usage of a knowledge modeling or any other modeling approach as well as having a behavior theoretic foundation in the design of their intervention. This is because self-management is problem-based [3], [18] and knowledge is ultimately intended to assist in problem solving [34]. Knowledge is used by an agent, human or non-human, for the purpose of reasoning to solve some sort of problem [34]. For humans, this internal process of reasoning is not possible without an internal cognitive representation of the external world. In the same manner, knowledge model is the analogue of internal cognitive representations in case of non-human agents. In such cases, the ultimate end is to allow appropriate processes to algorithmically reason over the embedded knowledge in the knowledge model to simulate intelligent behavior. The reasoning process produces new knowledge to answer questions or solve problems [34].

The context of this literature review is knowledge modeling. A knowledge modeling approach tends to signify importance of organizing knowledge in terms of interconnected relations between concepts governed by rules and axioms. Recent advances in knowledge representation formalisms offers flexibility and expressiveness in modeling a domain. Perhaps the biggest advantage is that a modeling approach is amenable to subsequent model improvement [35, Sec. 3.2]. Other advantages that have been cited for the knowledge modeling approach are:

1. **Formalization of domain knowledge** enabling domain experts to get involved in improving and subsequently validating the contained knowledge. Further, this formalized representation is computer-interpretable giving us the advantage to reason over this knowledge by means of appropriate reasoning algorithms.
2. **Knowledge reuse and sharing** across different systems by being represented in a formal manner is another advantage. Domain knowledge models can be used in a different context given an appropriate process model thus promoting knowledge reuse.
3. **Subsequent model improvement** because formal representation of knowledge lends itself better to later improvements through incorporation of new facts and information in the model.

We argue that the above reasons provide enough incentive for one to justify pursuit of a knowledge-based solution in a health-based context to the problem of promoting self-management of chronic illnesses. As a first step, keeping this particular perspective in mind, we review literature for existing technological solutions addressing the above problem. We scope the usage of computing technologies in the design and implementation of various self-management interventions. Particularly we focus on existing works that have informed their intervention design using Behavior Change Theories (BCTs). We only considered computerized behavior theory based interventions whether characterized as self-management or not. So, it could either be a behavior change intervention (e.g. for smoking cessation) or a self-management intervention (e.g. for diabetes). It is worth noting that the terms like *self-care*, *patient education*, *health coaching* are often used in place of self-management [36]. While conducting the review, we did not discriminate studies based on their definition or usage of the term self-management. We have emphasized *computerization* and *behavior change theories* to the extent that we dropped studies not explicitly specifying their behavior-theoretic foundations. Only English language articles published within the timespan of 1990 to date were considered. We present a quick overview of all the studies reviewed characterized by their behavior-theoretic commitments in Table 3.1 which is then followed by a discussion.

Table 3.1: Computerized behavior change interventions

Behavior Theory	Study References
Social Cognitive Theory	[37]–[44]
Transtheoretical Model (Stages of Change)	[44]–[57]
Self-Efficacy Theory	[48], [58]–[62]
Theory of Planned Behavior	[53]
Motivational Interviewing	[46], [47], [63]
Cognitive Behavioral Therapy	[64]–[66]
Health Belief Model	[45], [46]
Attribution Theory	[40], [46], [63]
Self-Determination Theory	[46]
Theory of Relapse	[46]
Social Support Theory	[60], [61]
Rothman's Behavior Change Process	[6]
Regulatory Focus Theory	[6]
Health Promotion	[51]
Integrated Theory of Health Behavior Change	[67], [67]

Web and mobile-based self-management interventions are separately summarized in Table 3.2 below.

Table 3.2: Web and mobile based behavior change interventions

Behavior Theory	Study References (Web)	Study References (Mobile)
Social Cognitive Theory	[42]–[44]	
Transtheoretical Model (SoC)	[44], [49]–[57]	
Self-Efficacy Theory	[58]–[62]	
Theory of Planned Behavior	[53]	
Cognitive Behavioral Therapy	[64]–[66]	
Rothman's Behavior Change Process		[6]
Regulatory Focus Theory		[6]
Health Promotion	[51]	
Integrated Theory of Health Behavior Change	[67]	

Many of the above studies were essentially educational interventions. We considered *computerized* interventions to have a significant computer-based component that a person can interact with either *online* or *offline*. For example, in a study by Hageman [68] a computer-tailored newsletter was provided to the patients. We considered this a *computer-tailored* intervention, not a *computerized* intervention. We also distinguished between between *Internet-delivered* and *Web-based* interventions. Internet-delivered is used when the Internet is primarily used as a delivery medium. Web-based refers to the fact that the intervention is designed to be used online. For example, the same study by Hageman [68] used the Internet just as a delivery medium for a computer-tailored newsletter. Even though they did employ computer systems in their intervention, from our standpoint, this was considered an Internet-based intervention and not a web-based intervention.

Some of the studies reported no improvements in Self-Efficacy as a result of their intervention. All of there studies were mainly educational in nature, having just an online educational portal and hoping to enhance self-efficacy. As highlighted by Bandura, knowledge and education are important determinants of the behavior change process but they alone are not sufficient to change the behavior [10].

In [41], Facebook® messages were used to deliver "expanded behavioral lessons" as an educational intervention. They were posted on their Facebook® group's wall by the study administrator. Participants had access to a "goal-setting tool" and a "PA diary". They did not explicitly mention any modeling approach used in the designing of their tools. Though they did have assessment tools built into their tools. Overall, it was more of an educational intervention.

Catherine et al. in [62] described an online diabetes companion, a self-management website based on Self-Efficacy principles. It was also education-oriented with frequent alerts and reminders from study administrators. The focus seemed to be more on behavior theory informed website design. The study did not mention the details of modeling of the patient education content in a way that incorporated Self-Efficacy principles. Website design seemed to be more in focus. The website usage by participants was measured as a metric to assess the success of the study.

In [46], a web-based asthma self-management tool program called "Puff City" targeted adults with asthma. They mentioned a number of behavior theories—Transtheoretical Model, Health Belief Model and aspects of Motivational Interviewing—being used to adapt content from authoritative guidelines. They mentioned the use of computer algorithms providing theory-driven feedback but did not provide details of its working, and how did they model the content taken from guidelines according to the principles of these behavior theories. Which behavior theory constructs the modeled content was targeting to change and how their modeling achieved that. Answers to all these questions which are pertinent to us in the context of this thesis were missing.

[53] featured a regular physical activity intervention for adults aimed at promoting an active lifestyle to meet minimum daily activity requirements. It was computer-tailored and delivered over the Internet. They sent "reinforcement e-mails" again highlighting the fact that it was more education focused and did not mention any modeling details of their intervention.

[67] took an educational and action-oriented approach and their content was based on international guidelines. They provided recommendations for increased calcium intake and they had a website mainly for information providing purposes and an application

designed for hand-held computers, especially designed to enhance self-regulation behaviors. They had a library of tailored messages that were matched to individual's calcium intake levels of very low, low or adequate intake of calcium. These messages were modeled using a if-then-else rules which were then manually checked the consistency and coherence of all the permutations of messages to different calcium intake levels.

The above overview of some salient studies suggests a lack of a robust modeling approach or at least a lack of its mention in the writing. A modeling approach would entail careful specification of links to the underlying behavior-theoretic foundation and modeling of a subsequent process model that harness the power of those theories through those links. A knowledge modeling approach, in particular, would also allow embedding of domain knowledge in a manner that it can be reasoned upon later using appropriate reasoning algorithms. Most of the reviewed studies did not make use of any such modeling or knowledge modeling approach. In that context, this thesis is an attempt to address this gap by presenting a proof-of-concept system built using a knowledge modeling approach.

3.1.1 Section Summary

We reviewed literature related to behavior theory based self-management approaches and highlighted some of the studies. We also outlined our contentions from purely a knowledge management perspective. Most of the studies reviewed above did not outline details of how they modeled the patient education content incorporating Self-Efficacy enhancing strategies. If they did so, it was not explicitly mentioned. We contend that a knowledge modeling approach, by means of allowing reasoning over the contained knowledge, is a better modeling approach. This review was helpful in highlighting the usage of computing technologies alongside behavioral theories in self-management interventions. In the next section, we present a detailed account of knowledge modeling and engineering and knowledge based systems before proceeding to our research methodology.

3.2 Knowledge Engineering and Knowledge Based Systems

Knowledge engineering is "*the process of integrating knowledge into computer systems that are designed to imitate problem solving that normally requires human experts...*" [34]. Computing systems that integrate knowledge are known as **knowledge-based systems (KBSs)** [34]. Knowledge engineering as a discipline is concerned with the systematic activity of developing knowledge-based systems [69].

Such a system is minimally composed of two very essential components:

- A ***knowledge base*** containing domain knowledge in a highly structured form encoded in some *knowledge representation formalism*. The entirety of the represented knowledge are known as *asserted facts* or *asserted knowledge*.
- A ***reasoning engine*** with mechanisms that support automated reasoning. Reasoning is the task of *deducing* new facts from already asserted facts. This deduction process is called *inference* or *entailment*. The new facts deduced from the asserted facts are termed the inferred or entailed facts. There are different ways of reasoning over asserted knowledge like *forward* and *backward* reasoning. A reasoning engine can employ multiple means to entail new facts from asserted facts [34].

Knowledge engineering should not be confused with knowledge management. Knowledge management is business- or organization-focused and defines the framework within which knowledge engineering activities are carried out. Knowledge Managers discover the knowledge needs of an organization required for informed decision-making and action and incorporate them within the knowledge management framework by specifying policies. Knowledge Engineers strive to meet those enterprise knowledge management needs by concerning themselves with the engineering details of acquiring and encoding the necessary knowledge in the enterprise knowledge-based system [70].

At this point, it is but customary that we define the term "*knowledge*" for the sake of reader's comprehension.

3.2.1 Knowledge

The defining characteristics of knowledge distinguishing itself particularly from information are that:

- It is *actionable* information—information that can be readily acted upon.
- It is embedded in an *agent* that can produce some *effect* in the world [34, pp. 47–49].
- It is highly *context-dependent* in nature [34, pp. 47–49].

It is broadly classified into two main types: *declarative* and *procedural* [34].

Declarative knowledge is *factual* in nature declaring what things are e.g. *a man is a human* or *a dog has a tail* [71]. It states something that can be *true* or *false* in the world. It can be verbalized using descriptive or propositional sentences, hence also known as *descriptive* or *propositional* knowledge [34].

Procedural knowledge is *actionable* in nature, and therefore, may not lend itself to proper verbalization. It manifests itself as a skill that pertains to doing something. It is also referred to as "know-how" in common usage [34].

In short, procedural knowledge is the *skill to do something* compared to declarative knowledge which is *knowledge of facts*. Their different nature is readily appreciated by considering the example of driving a car. One may know the purpose of handbrake, where to put hands on the wheel, but unless one successfully applies all this knowledge in actually driving a car, one cannot claim that I *know how* to drive a car.

Understanding this distinction is important because the type of knowledge dictates the choice of knowledge representation formalism in developing knowledge based systems.

3.2.2 Steps in Knowledge Engineering

A KBS is an end-product of a knowledge engineering activity that involves *capturing*, *modeling*, and appropriately *representing* the knowledge to be used in the system. Various phases in the knowledge engineering activity are thus aptly named as [70]:

1. Knowledge Acquisition
2. Knowledge Modeling
3. Knowledge Representation

3.2.2.1 Knowledge Acquisition

It is the process of identifying the requisite expertise needed for solving a problem in a given domain and collating that expertise in a way that is amenable to knowledge modeling [34]. This expertise can either be obtained from a *human* expert or gathered from *non-human* sources.

When the expertise is gathered through direct interaction with a human expert then this process is termed *knowledge elicitation*. With time, various techniques have been developed to assist this process. Some of the popular ones include: *interviewing*, *brainstorming*, *protocols*, *laddering*, *observations*, *concept sorting*, and *repertory grids* [72], [73]. These techniques are designed to facilitate systematic gathering of the requisite expertise from human experts, and even tap into the areas of consciousness holding the knowledge in its tacit form [69]. An excellent example of the tacit form of knowledge would be procedural knowledge that is manifested only when the skill is being executed.

On the other hand, when the requisite expertise is gathered from non-human sources—electronic documents, databases, the Internet—then this process is termed *knowledge discovery* [34].

Nevertheless, the knowledge acquisition phase culminates when the requisite domain expertise for solving a particular problem in the domain has been gathered and is now ready to be modeled.

3.2.2.2 Knowledge Modeling

Knowledge acquired in the knowledge acquisition phase needs to be organized and represented in some structured form. Knowledge modeling is the activity of *transforming*, *shaping*, and *organizing* the acquired knowledge in a way that it remains faithful to the domain it captures but is representable in some knowledge representation formalism [34]. The resulting end-product of this activity is called a *knowledge model*.

Traditionally the development of knowledge-based systems assumed a **transfer approach**, whereby human knowledge was supposed to be transferred from the human mind to a knowledge-base as is [69]. Later this assumption proved to be false with the appreciation of the role of *tacit knowledge*,[1] shifting the paradigm to a **modeling approach**. The modeling approach views development of a knowledge-based system as constructing a computer model rendered with the problem-solving capabilities comparable to a domain expert. The modeling approach does not attempt to simulate the cognitive processes of the domain expert in order to capture the problem-solving capabilities in a knowledge-driven system. The reader should bear in mind that subscribing to a modeling paradigm leads to some inevitable consequences that are [69]:

- A knowledge model becomes an approximation of the reality. Like any other model, there will always be room for improvement [69].
- Knowledge modeling becomes a *cyclic process*. New observations will dictate modifications in the already constructed model. Contrariwise, the model will guide further acquisition and refinement of the contained knowledge [69].
- Knowledge modeling becomes inherently *subjective* in nature—subject to the interpretations of the the knowledge engineer—thus highlighting the need for rigorous evaluation of the model with respect to the reality being modeled.

Previously acquired knowledge, after having modeled, is now ready to be represented in some *machine-interpretable formalism* for serving the very purpose of automated reasoning.

3.2.2.3 Knowledge Representation

Knowledge representation is the activity of hosting the knowledge model in some machine-interpretable formalism. In humans, reasoning happens internally inside the cognition about the entities that exist externally in the world. Our cognition generates internal representations of external entities and use them as surrogates for reasoning purposes. Any operation that our cognition performs on this internal representation

[1] "…knowledge [that] is often not explicitly describable by the people who possess it…" [73].

can be translated to some action on the corresponding entity in the world [74]. If these internal representations are encoded in a standardized symbol system that has a shared understanding among a wider group of agents, then it can also act as a means of communication. In fact, *natural languages* are one of these formalisms widely excepted among humans as a means of communicating internal thoughts.

Similarly, the modeled knowledge needs to be represented in some representation formalism inside a computing system for it to be manipulated later. *Knowledge representation* is the process of expressing the knowledge model using a *non-ambiguous*, *formalized*, and *structured* symbol system [75]. By being represented in such a formalism, the captured domain knowledge would become *interpretable* by an appropriate *reasoning engine*. Thus the sole purpose of representing knowledge is to enable *automated reasoning* over it.

Even though natural languages can be used to represent the knowledge model, but their extreme expressiveness comes at the cost of allowing ambiguity in interpretation. For automated reasoning purposes, computing systems need the knowledge model to be represented in a non-ambiguous formalism allowing only one interpretation. Some of the *computer-friendly* formalisms that have been developed over time are: **semantic networks**, **frames**, **description logics**, **conceptual graphs**, and **fuzzy logic** [34]. They allow representing knowledge with variable levels of expressiveness and no ambiguity. A detailed discussion about these formalisms is beyond the scope of this thesis, however, the next section presents *ontologies* which are based on description logics.

3.2.3 Section Summary

The knowledge captured and modeled is to be represented in some sort of knowledge representation formalism. The choice of formalism is an important one because it would either promote or restrict knowledge sharing and reasoning. The kind of inferences a KBS can entail are directly tied to the expressiveness and limitations of the knowledge representation formalism used. In the next section, we will discuss the *Web Ontology Language (OWL)* in detail which is a knowledge representation formalism based on description logics.

3.3 Ontologies

Ontologies are the dominant knowledge representation formalism in use today owing to the rise of the *semantic web*. They are used to encode shared and common vocabulary of a domain that is understood both by humans and computing systems [69].

3.3.1 Definition

Although the term "*ontology*" has been in use over a millennium, the current meaning of the word has been popularized by extensive research in the field of Artificial Intelligence (AI). The term is formally defined as "**...[a] formal, explicit specification of a shared conceptualisation**" [69]. Every *concept* in a domain whether concrete or abstract, every *relation* among these concepts, and every *constraint* upon these concepts and relations are explicitly specified in some machine understandable symbol system thus rendering them *formal*. The process of specifying concepts, relations among these concepts, and constraints upon these concepts and relations is called *conceptualization*. This conceptualization usually represents a common understanding of the domain implying that this understanding is shared by a larger community of experts—also known as *domain experts* or *subject matter experts* [69].

An ontology is not merely a computer representation of some domain but, by its very definition, represents some consensus and offers some perspective. It represents some degree of consensus among the domain experts regarding the knowledge of that domain [69]. It offers a perspective, a set of glasses that taints one's view of the world in a certain manner when talking about that domain. Those adopting this perspective are said to have an *ontological commitment* [69].

3.3.2 Ontology vs. Terminology vs. Controlled Vocabulary vs. Taxonomy

The terms in the subsection title are sometimes confused with each other but they have subtle differences in their meaning.

A **terminology** is just a naming scheme. It is the act of specifying or choosing syntax for talking about entities in a domain.

A **vocabulary** associates the terms in a terminology to their meaning. In grammar parlance, it associates *syntax* to *semantics*. Natural language vocabularies are usually ambiguous because they contain *homonyms*—same words with a different meaning—among other reasons. Humans are able to decipher the correct meaning by considering the ambient context. For computing purposes, use of **controlled vocabularies** is a norm which are *non-ambiguous*, *restricted* subsets of the terms in a natural language vocabulary. They are usually used by librarians to index and catalog library items to facilitate future search and retrieval. A familiar example of a controlled vocabulary, for many, would be *Medical Subject Headings* (*MeSH*) which is used by the National Library of Medicine (USA) for indexing journal articles in the life sciences domain.

A **taxonomy** is concerned with classifying entities according to some scheme. Usually it introduces some sort of parent-child hierarchy between the terms representing entities in the world.

Ontologies take some characteristics from all of the above and incorporates new one of their own. It denotes a specific *name* (syntax) and a precise *meaning* (semantics) to every entity in the domain excluding any other use of the name than prescribed. Ontological definitions do not just describe the meaning of the concepts in the domain—like a dictionary or a lexicon—but they adorn the terms of the domain with precise meanings. By defining the terms, they behave like a controlled vocabulary and facilitate taking about the domain in precise terms. Apart from prescribing the terminology, computational ontologies arrange those concepts in some hierarchical order where they appear to bear some resemblance to a taxonomy. While taxonomies only support parent–child relations, ontologies support many more. In addition to the terminological, taxonomic, and controlled vocabulary like characteristics; they capture the constraints of the domain through *description logic based axioms*. Thus, ontologies possess a very rich internal structure making them an ideal candidate for representing knowledge models [69].

3.3.3 Types of Ontologies

There are different types of ontologies based on their *level of generality* and the intended *scope* [34], [69].

- **Generic Ontologies** describe domain-independent concepts like events, time, space, process, behavior and so on [34]. Because these concepts are common across all domains, therefore, these ontologies are also known as *general*, *upper*, *foundational*, *top-level*, or *core* ontologies [34]. Some examples of such ontologies are: *Cyc* [76], *Dublin Core*, and *Suggested Upper Merged Ontology* (*SUMO*) [34].
- **Specific Ontologies** represent concepts particular to some domain, a specific application area, a particular task or activity, or some particular method [34]. They are usually further sub-divided as:

  - **Domain Ontologies** which model abstract concepts and concrete entities related to a particular domain e.g. medicine or computer science [69]. These type of ontologies usually encode static knowledge devoid of the problem solving context.
  - **Task or Method Ontologies** which "*...provide a reasoning point of view on domain knowledge*" by modeling tasks or methods in a particular domain [69]. They solve the "*interaction problem*[2]" by specifying the interactions between problem-solving and domain entities using assumptions [69].
  - **Application Ontologies** are combination of a domain ontology and some particular task or method ontology, thus packaging a complete solution to a particular problem in some domain [69].

3.3.4 Role of Ontologies in Knowledge Engineering

A knowledge-based system fundamentally comprises of domain and problem-solving knowledge [69]. The main role of ontologies in the knowledge engineering process is to allow capturing of domain knowledge in domain ontologies and problem solving expertize in task or method ontologies [69]. An ontology is just a schema by itself but becomes a *knowledge-base* when combined with instances.

[2]"... domain knowledge cannot be independently represented from how it will be used in problem solving, and vice versa" [69]

3.3.5 Web Ontology Language (OWL)

The Web Ontology Language (OWL) [77] "was developed from an amalgamation of the DARPA-funded DAML language [78] and the EU-funded OIL language [79]" [80]. Because of its ties to the the Web platform, it has become the dominant choice for knowledge representation, as it also promotes knowledge sharing, dissemination and reuse. OWL Version 2 is the latest as of this writing.

Web ontologies are specified in one of the standard web ontology languages, either RDF(S) or OWL, and published on the web. The OWL standard mixes the *terminological* and the *assertional* knowledge and regard such artifacts as ontologies. Terminological knowledge are "the terms used to describe data, and the formal relations between these terms" [81]. Assertional knowledge are "[the] terms describing individuals and ground facts asserting the state of affairs between these individuals" [81]. Even though such ontologies are not accepted as proper ontologies by some [82], this thesis embraces the standard OWL practice and regards "ontologies as artifacts encompassing both the terminological as well as the assertional knowledge" [81].

3.3.5.1 Syntax

The primary syntax for OWL 2 ontologies is RDF/XML-based and is required to be supported by all OWL 2 tools. A more human-readable *Manchester Syntax* is also supported.

3.3.5.2 Semantics

OWL 2 has *Direct Semantics* as well as *RDF-based Semantics*[3]. In direct semantics, the ontology structure is used directly for reasoning using *SROIQ Description Logic* [83]. Description Logics are a family of knowledge representation formalisms based on a subset of First Order Logic. SROIQ is one of the members this family with good computational properties—meaning reasoning efficiency.

In RDF-Based Semantics, instead of using the ontology structure directly, it is first

[3]Resource Description Framework

mapped to an RDF graph and then that graph is used for doing the actual reasoning [84].

The reader is encouraged to consult the cited sources to learn more about the semantic processing of OWL 2 ontologies, as a detailed discussion is beyond the scope of this work.

3.3.5.3 OWL Profiles

OWL also has a concept of profiles that standardizes some well-known trade-offs between *expressiveness* and *reasoning efficiency* for practical reasons [85]. The three variants of OWL having different computational properties are: *OWL 2 EL*, *OWL 2 QL*, and *OWL 2 RL*.

3.3.6 Section Summary

The modeled knowledge is of little use if it cannot be reasoned upon. For automated reasoning purposes, the modeled knowledge must be represented in some representation formalism with good computational properties. The Web Ontology Language (OWL) is one such formalism which balances *knowledge expressiveness* and *reasoning efficiency*. It is based on description logics formalism which itself is a decidable subset of first order logic. It has gained adoption with the advent of the semantic web approach and has earned a W3C recommendation status. This makes OWL an obvious choice for knowledge representation purposes.

3.4 Concluding Remarks

This chapter concluded the background of this thesis by introducing the reader to the *knowledge-based* approach to systems engineering and the importance of knowledge representation formalisms in automated reasoning. Further, it briefly talked about the *Web Ontology Language (OWL)* which is the predominant knowledge representation language in use today. Lastly, it presented an overview of work that has been done in computerization of behavior change interventions.

CHAPTER 4 RESEARCH METHODOLOGY

This chapter presents our research methodology—the sequence of steps undertaken to address the problem statement—with a strong emphasis on inspiration and rationale. Our focus will be on the conceptualization of a modular self-management framework with firm grounding in Social Cognitive Theory. Subsequent chapters will present the implementation details and the evaluation strategy.

Figure 4.1 shows the steps in our research methodology. Details follow in the proceeding sections.

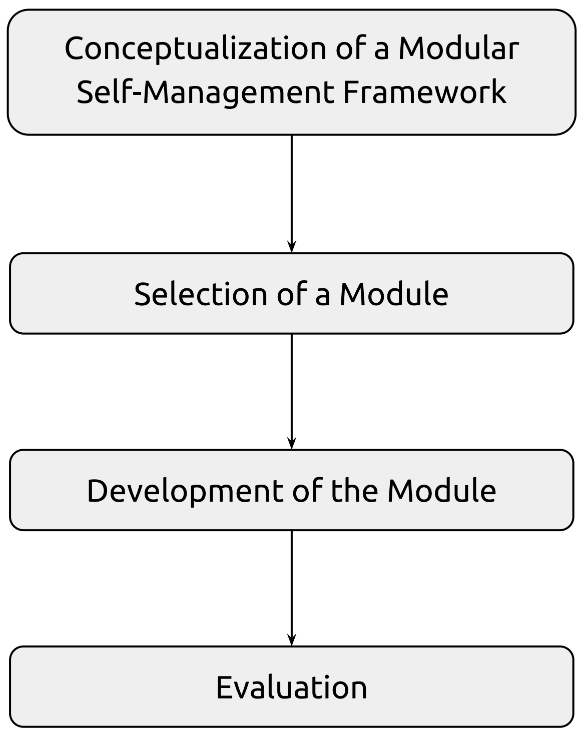

Figure 4.1: Steps in our research methodology

4.1 Conceptualizing a Modular Self-Management Framework

Because chronically ill patients are largely responsible for managing their condition 24/7 and lifestyle interventions are analogous to behavior change interventions, we lay foundation of a *self-management* framework that is in harmony with the core tenets of *Social Cognitive Theory* (*SCT*).

4.1.1 Socio-Cognitive Determinants of Behavior Change Process

Bandura has outlined the way in which SCT can be utilized to promote health and prevent disease [10]. Following decades of research, he proposed a core set of determinants and the ways in which they can be translated into effective health practices [10]. These core determinants include:

1. **Knowledge:** It acts as a precursor for behavior change. Having knowledge of health risks and benefits of different healthful practices creates the precondition for behavior change.

2. **Perceived self-efficacy (SE):** An enhanced sense of Self-Efficacy is the basis of the belief that one can exercise control over one's health habits and the surrounding environment.

3. **Outcome expectations:** Expectations about the costs and benefits of different health habits can motivate one to take action or demotivate one to not.

4. **Health goals:** *Long-term* goals set the course for personal change without micromanaging behavior in the present. *Short-term* goals help people materialize long-term goals by guiding action in the here and now.

5. **Perceived facilitators and socio-structural impediments:** Different barriers and facilitators can improve or impede the behavior change process.

The translation of health knowledge into healthful habits is heavily mediated through perceived Self-Efficacy which plays a pivotal role in the behavior change process [10].

4.1.2 Centricity of Self-Efficacy in the Behavior Change Process

A pertinent question one may ask: *why just focus on self-efficacy out of all the core determinants?* Bandura's decades of research has generated ample evidence in favor of SE as playing a central role in the causal mechanism mediating behavior change. Figure 4.3 depicts Self-Efficacy affecting one's behavior directly and indirectly via other behavioral constructs [10].

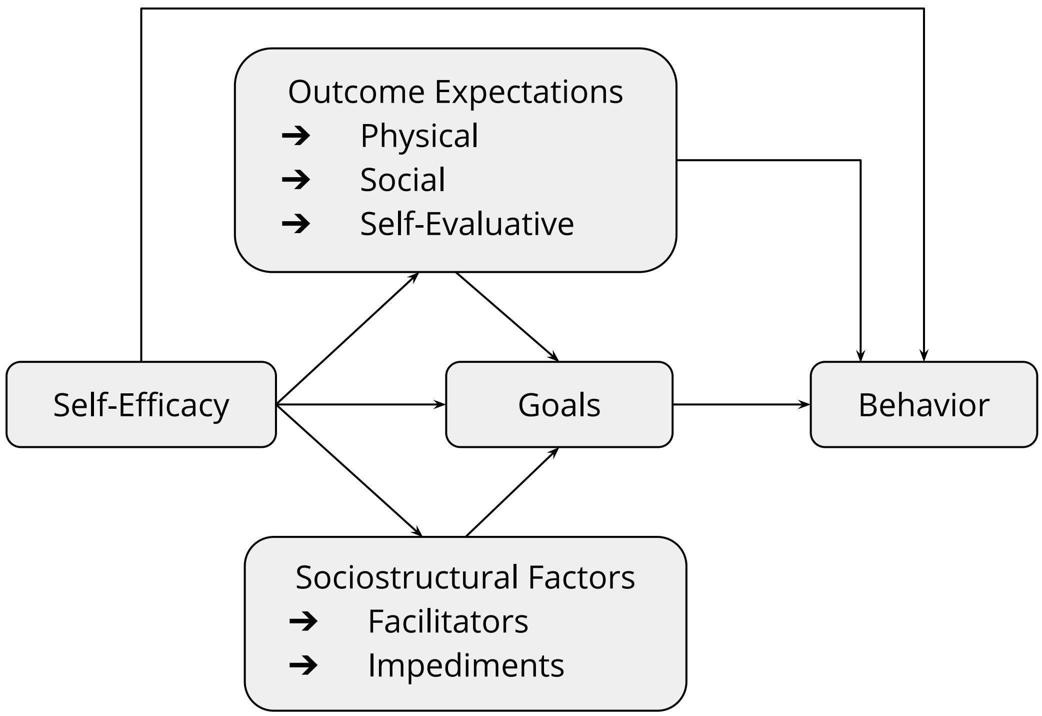

Figure 4.2: Central role of self-efficacy

Individuals having a high sense of Self-Efficacy usually bear *positive outcome expectations*, which promote willful execution of the desired behavior. Such people also tend to set higher goals and display increased commitment, effort and perseverance to achieving them. They perceive barriers as challenges to be mastered rather than something to be avoided [27], [28]. Every other behavioral determinant is influenced by a person's sense of Self-Efficacy directly or indirectly.

4.1.3 SCT-Inspired Self-Management Framework

A comprehensive self-management system, well-grounded in SCT principles, will embody all or most aspects of the core determinants described earlier. Given the centricity of the Self-Efficacy construct, we argue that enhancing an individual's Self-Efficacy is an effective way to promote regularity in the performance of the behavior, thus leading to effective self-management of the chronic illness in the long run.

To this end, we abstracted *high-level tasks* from this minimal description of the core determinants, in a way that they can be easily tied back to the core determinant they fall under. Figure 4.3 shows the transition from the core determinants to high-level tasks elaborated with descriptions.

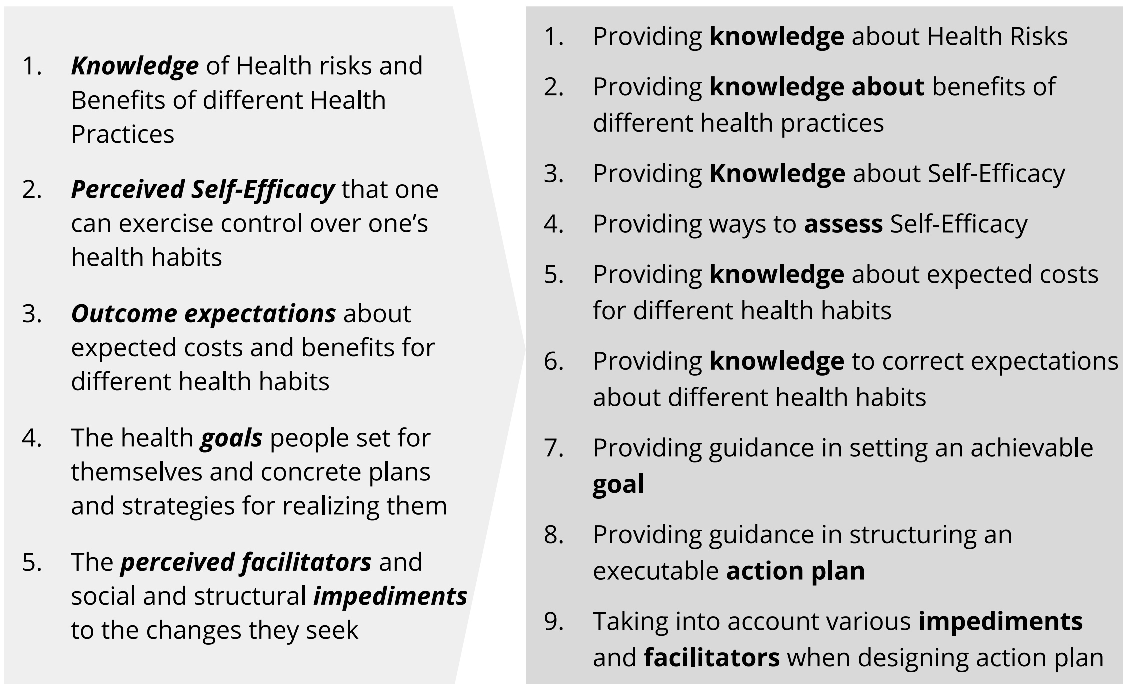

Figure 4.3: Abstracting high-level tasks from the core determinants

One can readily see a common thread that ties these high-level task descriptions together, as well as a natural boundary that delineates them. We dissected the thread at its natural boundaries creating separate modules with focus concentrated on one particular aspect. This lead to the conceptualization of the following modules making the core of the self-management framework that we propose in this thesis.

1. **Patient Education Module** is focused on providing *knowledge* about different aspects of self-management to the patient because knowledge is known to provide the necessary impetus for behavior change.

2. **Assessment Module** is focused on providing ways for *objective assessment* of Self-Efficacy and other relevant measurements.

3. **Action Planning Module** is focused on assisting one in formulating a *SMART*[1] goal and subsequent guidance in construction of an *achievable* action plan; while giving due consideration to facilitators and impediments of various kinds.

4. **Communication Module** is focused on helping individuals connect with a health-care professional, preferably a person's family physician, to cater the need for specific medical advice if needed. Even though the need for this module is not obvious from figure 4.3, the importance of better patient-physician communication is very well established.

Modules are supposed to be *self-contained* and *implementation-independent*. Figure 4.4 shows the proposed self-management system along with all the modules.

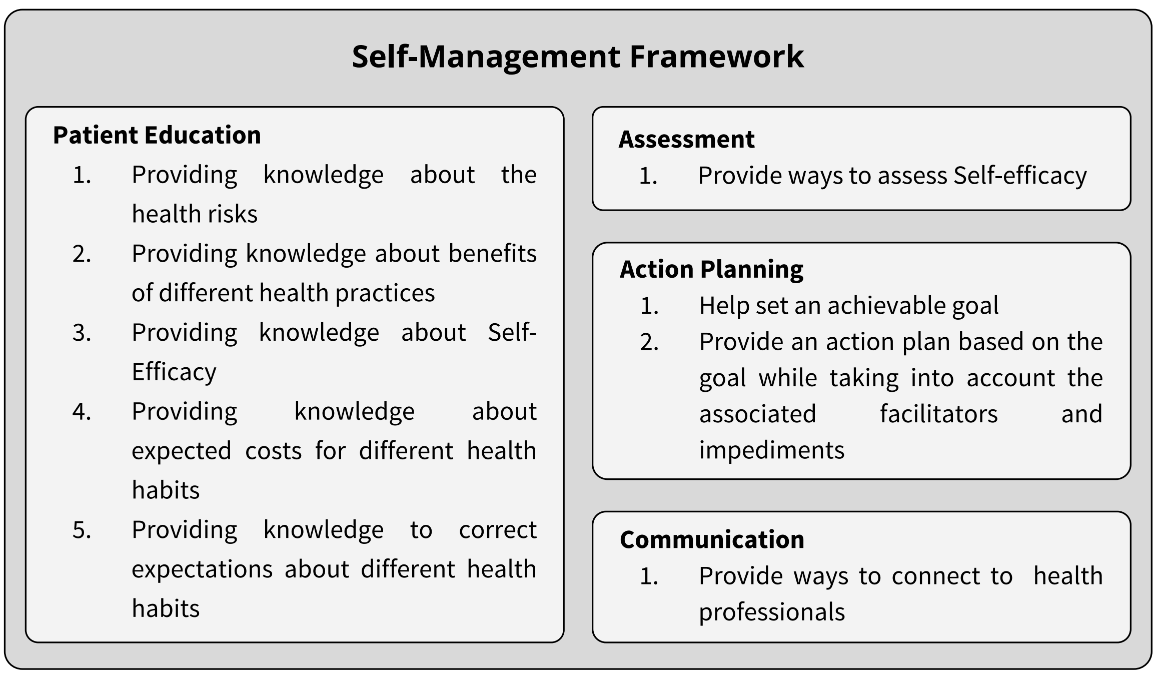

Figure 4.4: Proposed self-management framework

The strong link between *high-level task descriptions* and *core behavior determinants* gives our proposed self-management framework a firm grounding in *social cognitive theory* and, by extension, a behavior change theory.

[1]Specific, Measurable, Actionable, Realistic, and Time-bound.

4.2 Selection of a Module

Since the proposed self-management framework encompasses many facets of self-management, we restricted our focus on implementing one module in this thesis.

Traditionally there had been a focus on patient education [86]. Despite the importance of knowledge, as acknowledged in our framework through the inclusion of a module focused on patient education, it alone is not sufficient to bring about a change in behavior [7].

Furthermore, numerous studies have underlined the importance of goal-setting and action planning in changing behavior [33], [87]. Because our primary concern is changing behavior patterns, we decided to take this opportunity to address our primary concern. So, as a first step towards the realization of our proposed framework, we decided to take a performance-oriented approach and devised a strategy focused on *action planning* to enhance *self-efficacy* of the person.

4.3 Developing the Module

We have taken a knowledge-based approach to the design and implementation of the action planning module. The step-by-step details of the modeling approach is the topic of the next chapter. What follows in the next sub-section is the definition of the terms and a gist of the development strategy with focus more on the rationale behind this particular approach, without delving too much into the implementation details. It should be noted though that the *implementation-independence* nature of the modules in our framework enables the functionality of this module to be swapped with a totally different implementation, with the only restriction that the new implementation should be rooted in the social cognitive foundation.

4.3.1 Definitions

Some of the terms used subsequently should be interpreted as defined and described here.

Behaviors are related set of activities or tasks in some domain of human functioning.

Barriers are obstacles or impediments of any kind to the performance of some behavior.

Goal represents an intention to overcome a specific barrier. In the context of this thesis, we redefined the term "goal" for the purpose of facilitating our modeling process. The term "goal" as used in my conceptualization has no relation to the term "health goals" proposed by Bandura as one of the core determinants [10]. For our modeling purposes, we fixed the definition of the term "goal" to represent the intention of the user to overcome a specific barrier. As a consequence, any barrier can be rephrased as a goal implying that the individual aims to overcome the barrier at some time in the future.

Action Plan is a user-constructed weekly plan of performing some activity that the user intends or commits to adhere to in the following week. They correspond to *proximal goals* as per the terminology used in SCT. For a detailed account of how action planning came to be a behavior change tool, see chapter 2 §2.3.2.

An action plan is considered *good* if it possess the following properties [3], [30]:

1. It is action-specific.
2. It is something that one wants to do.
3. It is short-term, usually not more than a week.
4. It is achievable in a sense that it can be accomplished within a week.
5. It has good answers to *what*, *how much*, *when* and *how often* type of questions.
6. On a scale of 0–10 (not at all sure–absolutely sure), one confidently rates themselves at 7 or above. This rating is informed by Self-Efficacy theory [3].

Our process makes sure that the action plans constructed adhere to this brief and simple guideline. Any action plan that does not adhere to the above guidelines is considered a *bad* action plan.

Action Plan Suggestions are barrier-specific *solution strategies* to help overcome a specific barrier. They are intended to facilitate the process of constructing a *good* and *workable*[2] action plan. An individual is not bound to follow them, hence, they

[2] Achievable

are aptly termed suggestions.

While Action Plan Suggestion is a general suggestion to help one deal with a specific barrier, an *action plan* is a concrete plan to perform short, doable tasks that set one on the course to achieving the larger goal over time and can be accomplished in a relatively short time, ideally within a week. An *action plan suggestion* coupled with *action plan questions* act as a template for constructing quality action plans. An individual can customize it to their own needs and preferences to create a *concrete* action plan. Because every individual has different *time constraints* and subscribe to different *value systems*, so customizability has an important place in our solution approach.

Action Plan Suggestion Repository (APSR) is an organized collection of action plan suggestions.

Self-Regulatory Efficacy Questionnaire Repository (SREQR) is an organized collection of self-regulatory efficacy questionnaires.

4.3.2 Strategy for Implementing the Action Planning Module

Of the four sources of efficacy information, first-hand experience of successful performance is the most influential source for raising Self-Efficacy of an individual [27], [88]. Hence, we take a *performance-oriented* approach to enhancing self-regulatory efficacy in individuals. Our strategy utilizes *goal-setting* and *action planning* techniques to drive successful performance of activities [3].

A schematic diagram of Action Planning Module (APM) is shown in Figure 4.5. Broadly it consists of a *modeling* aspect and a *functional* aspect. The modeling aspect is based on SCT and houses all the content adapted as suggestions. Together they constitute the knowledge model. The *knowledge model* is an integral part of the APM and the details of its construction is the main discussion in the next chapter. On the other side, the functional aspect houses our strategy that operationalizes the knowledge model. We devised a performance-oriented process model as shown in the process layer of Figure 4.6. The *process model* is assumed and implied in our implementation and is designed as a sequence of steps to address the identified problem in a way that increases self-efficacy. It is inspired and adapted from Chronic Disease Self-Management Program (CDSMP) [3] which has been shown to be effective in the follow-up clinical trials [89], [90]. In short, the process consumes a patient profile as input and produces APSs. These APSs can potentially be taken up by an individual and turned into a concrete action plans through further customization. This customization of APS into an action plan is an important feature of our system. The concrete action plan has the potential to be monitored for feedback. This feedback can potentially be fed back to the knowledge model for subsequent adjustment.

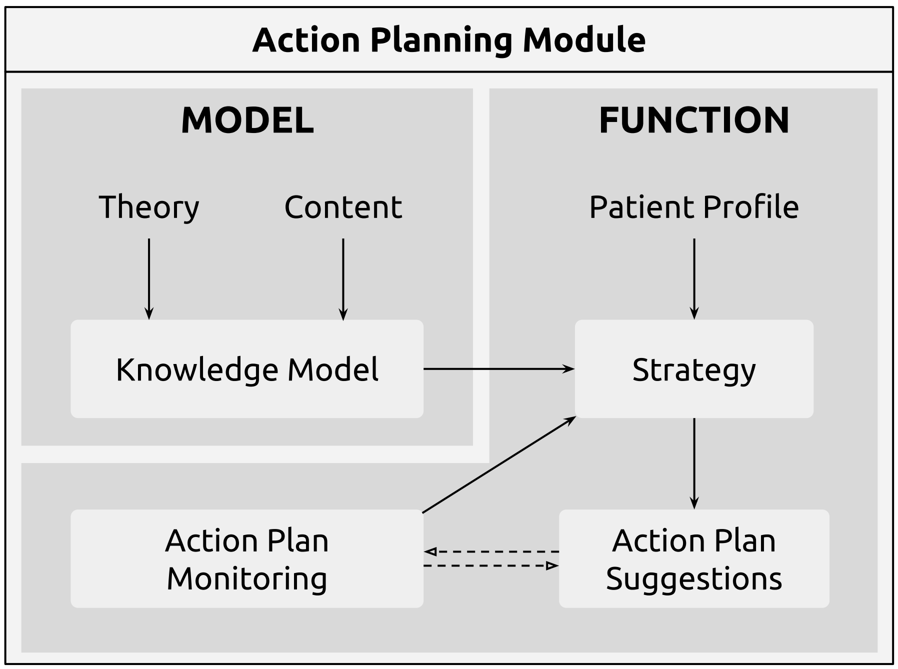

Figure 4.5: Action planning module implementation

The detailed strategy of APM implementation is shown below in Figure 4.6.

Major steps of our approach are:

1. **Identification of the Problem:** We identify the barrier by asking the person to fill in the self-regulatory Self-Efficacy questionnaire. These questionnaires are hosted inside APKM in SREQ-Repository. They help identify the problems which in our case are the barriers. These questionnaires are designed to assess whether the person will perform the desired behavior under certain circumstances or not.

   The advantage of identifying barriers using this approach are two-fold. *First*, we

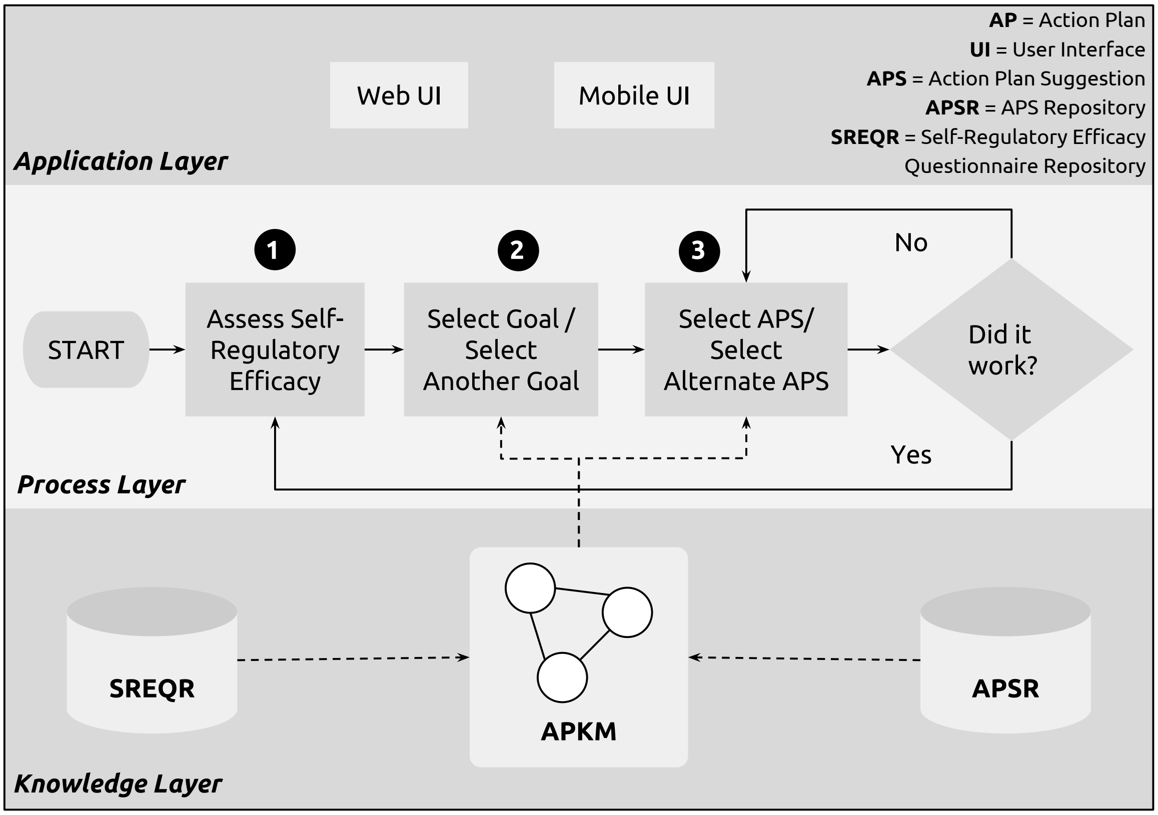

Figure 4.6: Internal architecture of APM

manage to assess the *efficacy level* and *efficacy strength* of the person for the behavior under consideration. *Second*, self-regulatory Self-Efficacy questionnaires assess a person's conviction to perform the behavior under increasingly challenging circumstances—challenging circumstances representing barriers to the behavior being considered—thus helping in identifying the most relevant barriers.

One might ask: *why are we selecting barriers from self-efficacy questionnaires?* Bandura has stated that *self-regulatory efficacy*—not *self-efficacy*—is concerned with the *routine performance* of a behavior under consideration. While constructing self-regulatory efficacy questionnaires, people are asked in pilot questionnaires and open-ended interviews about obstacles that prevent them from performing the behavior under consideration on a regular basis. The identified obstacles are later incorporated into the Self-Regulatory Efficacy Questionnaire which is intended to assess one's performance of that behavior under different challenging circumstances [26]. These challenging circumstances actually represent barriers to the performance of the behavior. So Self-Regulatory Efficacy Questionnaires actually codify common barriers to some behavior that were found to be statistically significant in validation phase of its construction.

Interestingly, SREQs are playing a dual role in our conceptualization of APM:

1. The role as an ***Assessment Tool***—to determine whether the patient should be moved to tackling the next barrier or not
2. The role as a ***Problem Identifying Tool***—to identify the problem of the user to target APSs accordingly.

2. **Goal Selection:** From the list of the barriers, the individual is then asked to select the ones they would be keen on addressing first. The *selected barriers* can be formulated as *goals* for the individual. These goals represent the challenges to the execution of the desired behavior. Having listed all the goals, the individual will be prompted to select one goal from the list to work on. Focusing on one goal at a time is one of the keys to successful self-management [3].

3. **Listing of Action Plan Suggestions:** Our knowledge-base of *action plan suggestions* will present suggestions to the individual to help achieve the goal—the *selected barrier*. The individual can choose any of the presented suggestions to work on.

4. **Action Planning:** The individual, taking any suggestion, will create a concrete action plan by answering four very specific questions about the activity under consideration. These four questions being: *what are you going to do this week?*; *how much you are going to do?*; *when are you going to do it? how often or how many days a week you are going to do it?* The action plan constructed as a result is what the individual is committed to doing this week.

   Good Action plans should not aim for more than 7 days [3]. By limiting the length of action plan to just a week, we are reducing the likelihood of failure completing the action plan.

The current implementation of APM and APKM largely assumes this process to hold true.

First of all, by following best practices from [3] to create action plan, we ensure the construction of quality action plans that have high likelihood of achievement. This has been demonstrated in the clinical trials conducted by Lorig et al. [58], [59], [90], [91].

If a particular APS fails for an individual, they will be urged to try out a different APS for the same goal or barrier. This highlights the fact there is no *one size fits all* approach when it comes to overcoming barriers to performance. The same APS for a specific barrier/goal may not work for different individuals. The process in [3] is designed to cater for failure situations and the individual is urged not to dwell too much if a particular strategy fails to work, but move on to try out other APSs for the same barrier.

4.3.3 Rationale for using this Implementation Strategy

A self-management system that conforms to Bandura's self-regulatory system principles would combine *proactive guidance* with *reactive adjustments* [25]. Proactive guidance in terms of helping one in setting a goal and constructing an action plan, thus establishing the standard to compare one's weekly performance against. Reactive guidance in terms of feedback about weekly performance to evaluate progress and appraise performance in relation to the set goal. The cognitive appraisal of performance against a standard—the *action plan* in our case—provides individual the necessary information that enhances or lessens the sense of efficacy. The most effective source of information to enhance Self-Efficacy is found to be the first-hand experience of success [28]. This *success* experience, no matter how trivial, has been proven to enhance self-efficacy. Our strategy emphasizes *action plans* because they provide an opportunity to the individual to gain *success* experience through engagement in performance which is theorized to increase Self-Efficacy of the individual over time. So, by promoting successive success experiences to overcome the barriers to some behavior—by helping to create achievable action plans—our strategy is geared towards enhancing individual's Self-Efficacy over time.

4.4 Evaluating the Module

Our evaluation strategy consists of *technical* and *scenario-based* evaluation of the developed model. Chapter 6 will present the results of our evaluation in detail.

4.5 Concluding Remarks

We presented the steps in our research methodology to address the problem statement with strong emphasis on rationale. We conceptualized a self-management framework that is firmly grounded in core behavior determinants put forth by Bandura after decades of research. We highlighted reasons for selecting the *action planning module* subsequently detailing the strategy and rationale of our implementation approach. Next chapter will further the discussion by giving an in-depth account of the implementation details.

CHAPTER 5 ONTOLOGICAL ENGINEERING OF ACTION PLANNING MODULE

This chapter gives a detailed account of the third step—*developing the module*—of our research methodology. The reader is referred back to chapter 4 for understanding the wider rationale of our solution approach. Our research work is scoped to developing the *action planning module* (APM) of our proposed framework, further narrowed to the *physical activity domain* for practical purposes. Specific terms including *behaviors*, *barriers*, *goal*, *action plan*, and *action plan suggestion* are to be interpreted as defined in chapter 4 §4.3.

We discuss in detail the construction of an *ontology-based knowledge model* using a *knowledge-based approach* and the *semantic web technologies*. Our knowledge-based solution approach is divided into three stages, which along with their corresponding *knowledge engineering phase* are listed below:

1. Content Gathering—*knowledge acquisition phase*
2. Conceptual Modeling—*knowledge modeling phase*
3. Ontology Engineering—*knowledge representation phase*

A detailed account of each stage follows in their respective section.

5.1 Content Gathering

Our solution strategy utilizes a *suggestion-based approach* to help individuals overcome *barriers*. We identified the need for two types of content to proceed with our implementation. This lead to the conceptualization of two main *content repositories* in our version of the implementation, namely:

1. Action Plan Suggestion Repository—***APSR***
2. Self-Regulatory Efficacy Questionnaire Repository—***SREQR***

APSR will house *suggestions* to overcome commonly encountered barriers to the physical activity performance. ***SREQR*** will house all the Self-Regulatory Efficacy Questionnaires from which we abstract barriers to the performance of physical activity. The reader is referred back to chapter 4 §4.2 if they find themselves questioning the relation between Self-Regulatory Efficacy Questionnaires and the barriers. The ***APSR*** and ***SREQR*** together form the *content backbone* of the APKM—serving as the source of *barriers* and *suggestions* as outlined at steps 2 and 3 in our implementation strategy.

5.1.1 Construction of APSR

This task was focused on gathering content about overcoming barriers to physical activity performance to mine suggestions from. The fact that self-regulatory questionaire has barriers encoded within, guided our content gathering strategy. This was largely a manual process in which we explored and gathered solutions to common barriers of physical activity from credible online sources.

5.1.1.1 Content Collection: Strategy, Scope and Sources

We listed some of the public health agencies (governmental as well as non-governmental) that have good patient educational material hosted on their official websites. We scrutinized the websites' content and gathered all the content related to physical activity published on their websites. Our focus were *tips* and *suggestions* that might help the patient in overcomming some of the barriers they face in the performance of physical activity. We specifically highlighted these sections in all the content that we collected. The highlighted sections of the content, manually scraped from the websites, were then subjected to an *APS selection criteria* to formulate action plan suggestions. The scope of the content collection activity, as mentioned before, was limited to the physical activity domain.

The websites serving as the canonical source of content for formulation of Action Plan Suggestions are listed in the Table 5.1 below.

Table 5.1: List of sources used to collect suggestions

Source	Web Address
WebMD	http://www.webmd.com/
MayoClinic	http://www.mayoclinic.org/
CDC	http://www.cdc.gov/
American Heart Association	http://www.heart.org/HEARTORG/

We now present the criteria for APS selection and formulation before demonstrating the conversion of the content gathered from these sources to actual *action plan suggestions*.

5.1.1.2 Criteria for APSs Formulation

For a *tip* or a *suggestion* to qualify as an *Action Plan Suggestion*, it had to conform to a certain criteria. The criteria was principally derived from the questions designed to help construct a good action plan. Having a structured criteria for APS formulation ensured that only quality APSs make their way into APSR. A tip or suggestion was considered a good candidate for inclusion in APSR if it lent itself as a suitable answer to the following questions:

1. What are you going to do this week?
2. How much will you do it?
3. When will you do it?
4. How often will you do it? (list days)
5. How sure are you that you can complete this entire plan? (0 - 10) (if below 7, revise the plan)

These questions are structured to enable *verbalization* of the action plan. Any tip or suggestion failing to provide a reasonable answer when subjected to any one of the above questions was immediately discarded from any further consideration.

5.1.1.3 APS Formulation Process

An example of an excerpt taken from **Mayo Clinic**[1] is shown below and the relevant content of interest is highlighted.

4. I'm too tired to exercise after work

No energy to exercise? Without exercise, you'll have no energy. It's a vicious cycle. But breaking the cycle with physical activity is one of the best gifts you can give yourself.

- **Try a morning dose of exercise.** Remember the suggestion to get up 30 minutes earlier to exercise? Hop on the treadmill or stationary bicycle while you listen to the radio or watch the morning news. Or step outside for a brisk walk.
- **Make lunchtime count.** Keep a pair of walking shoes at your desk, and take a brisk walk during your lunch break.
- **Be prepared.** Make sure you have comfortable shoes and loosefitting clothes for exercising. Take them with you to the mall or when you travel.

Figure 5.1: An excerpt from Mayo Clinic.

We subjected the highlighted content to the APS formulation criteria questions. We assess whether the highlighted portion of the content can provide reasonable answers to the criteria questions. An example of possible answers is shown in Table 5.2 below.

Table 5.2: Questions for APS selection.

Questions	Example Answers
What are you going to do this week?	Walk
How much will you do it?	10 minutes
When will you do it?	6:00 AM
How often will you do it? (list days)	3 times in a week (Mon, Wed, Fri)

[1]http://www.mayoclinic.org/

The reader should note that we have actually formulated a quite reasonable action plan by answering the criteria questions. The verbalization of all answers combined, for the above example, would be an action plan stating:

> *"I will walk for 10 minutes at 6:00 AM three times in a week on Monday, Wednesday, and Friday."*

Based on the answers to these questions, a different person might end up with a different action plan. This is intended by design because it gives a person an opportunity to construct an ation plan relevant to their specific situation and in line with their needs and preferences. This structured criteria with stress on verbalization was followed in gathering all APSs.

5.1.1.4 Deliverables

The output of this step was a list of APSs conforming to the criteria outlined above. See Appendix A for the full list of APSs we gathered in the course of this thesis, and the collected content that was used to formulate these APSs along with their online sources.

5.1.2 Creation of SREQR

Because of our focus on physical activity, SREQR as of now only contains one instance of SRE questionnaire in the physical activity domain developed by Bandura [26].

5.1.2.1 Content Sources

Bandura specifically addresses the construction process of Self-Efficacy scales in one of his papers [26]. At the end of this paper, he has an appendix of Self-Efficacy and self-regulatory efficacy questionnaires. For the purpose of this thesis, we gathered only the questionnaire concerned with the physical activity domain. The questionnaire is included in appendix B.

5.1.2.2 Barrier Formulation Process

Since it has been explained that self-regulatory efficacy qeustionnaires contain barriers—see chapter 4 §4.3.2—we considered all of the barriers. These barriers are coming from validated questionnaires, so their relevancy has already been established in the validation phase of the questionnaire construction process.

Table 5.3: Barriers from SREQ

No.	Barriers
1	I am often feeling too tired
2	I have too much workload
3	I cannot go out due to bad weather
4	I am feeling depressed and anxious
5	I lack support from my family or friends

5.1.2.3 Deliverables

The output of this step was a list of barriers abstracted from SREQ. A copy of full SRE questionnaire from which these barriers were extracted is included in appendix B [26].

5.1.3 Section Summary

This section presented an outline of our content gathering strategy that was used to collect content for the construction of APSR and SREQR. Their functional integration into APKM is the topic of the next section.

5.2 Knowledge Modeling

This is the conceptual modeling stage explicating the inner workings of the model in order to demonstrate how it addresses the problem statement. This step culminated in the production of a semantically explicit and executable knowledge model named as Action Plan Knowledge Model (APKM).

The materialized APKM consisted of the *user model* and the *suggestion model*, hence, the construction of the APKM will be discussed under two main themes: *user modeling* and the *suggestion modeling*. The *user model* defines the attributes that modifies the relevance of suggestions. The *suggestion model* is intended to filter the best APSs from APSR given a pre-defined user model. With this brief introduction to user modeling and suggestion modeling, we start the discussion by presenting the schematic diagram of the APKM.

5.2.1 Schematic Diagram of APKM

Figure 5.1 illustrates a high-level diagram of APKM showing the the inputs and outputs of the model. The intent of the APKM is best summarized in the question: *What APS is best for a Person given his Barriers?*

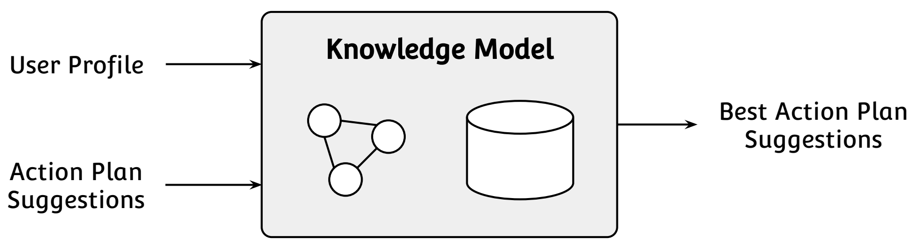

Figure 5.2: Knowledge Model

To *intelligently* answer this question, the APKM requires some sort of a user profile outlining their characteristics, and a repository of suggestions to select suggestions from. Therefore, the two necessary inputs to the APKM are the *User Profile* and the *APSR*. A ***User profile*** contains information about certain attributes of an individual. These attributes might affect their engagement in the physical activity behavior. The details of the its construction will be laid out in a later section. An ***APSR*** is a repository housing all the suggestions as explained in the previous section. Given an infinite number of APSs, APKM will filter the best APSs for a given individual while giving due consideration to the their needs and preferences outlined in the user profile. Thus, more information we have about the user characteristics—more variables in the user profile—the better the personalization of the suggestions. Contrariwise, there is very limited opportunity to personalize the suggestions leading only to the presentation of generic suggestions.

At this point, one may question the value of the **users** to **APSs** matching and filtering process? The value lies in the *consideration of APS by the user*. The chances of consideration are higher if APSs are contextualized to the users' needs, preferences and characterisitics. This contextualization furthers the probability of an APS being promoted to an *action plan* from a mere suggestion, thereby increasing chances of being acted upon. This is potentially projected to lead to success experiences and finally better chances of enhancing self-efficacy. This also prevents APKM from suggesting an APS that is ignored by a user owing to its irrelevance. This optimization of APKM to suggest APSs having a high likelihood to be taken up by the user potentially leading to increased success experiences gives APKM a behavior-theoretic foundation.

5.2.2 User Modeling

User modeling refers to the construction of a user profile which is one of the inputs to the APKM. A user profile holds information about characteristics of a user that might be helpful in filtering relevant APSs.

5.2.2.1 Determining Attributes for the User Profile

The domain effects the selection of attributes in the user profile. These attributes listed in Table 5.4 bear some significance in relation to physical activity since the scope of this work is restricted to the physical activity domain. Attributes were also considered based on their significance to APSs. Additionally some of the values for attributes had a certain criteria for the classification of their values which is included in the last column. Given a different domain, the relevance and selection of user attributes will definitely differ to some extent.

Table 5.4: Profile attributes in the user profile

Profile Attribute	Range of Possible Values
Age	Young, Adult, Old
Gender	Male, Female
Residence location	Rural, City, CityCenter
Profession	Student, Part-time, Full-time, Home-maker, Unemployed

Profile Attribute	Range of Possible Values
Body Mass Index (BMI)	Underweight, Normal, Overweight, Obese
Medical conditions	Musculoskeletal, Respiratory, Heart-related
Medications	Beta Blockers, Statins, Steroids
Physical disability	Yes, No
Time availability	High, Moderate, Low
Indoor exercise equipment	Yes, No
Gym membership	Yes, No
Sports (intensity)	High, Moderate, Low
Friend availability	Yes, No

The information about these attributes will be gathered from the user. These attributes will be presented to the user in a question form along with the possible answers. The answers to these questions will help us construct a valid user profile.

The significance of these attributes in relation to the physical activity and APSs is shown in the table below.

Table 5.5: Significance of attributes in relation to physical activity

Attribute	Significance
Age	May be significant by it's association with some medical conditions or medications.
Gender	In women, normal physiologic states like pregnancy may affect their physical activity levels.
Residence location	Proximity to recreational facilities and workout centers may positively affect an individual's physical activity level by way of convenience and accessibility.
Profession	Some occupations like office work and transportation may necessitate sitting for an extended period of time with minimal physical effort whereas other occupations may indicate higher activity levels like heavy lifting in case of movers and walking for distances in case of letter carriers.

Attribute	Significance
BMI	Individuals with higher BMIs, especially in the morbidly obese category, may have limited options of physical activities. They may benefit most from simple activities initially.
Medical conditions	Some conditions may prevent individuals from participating in regular physical activity. Musculoskeletal injuries and disease are a prime example of that. For example, patients with knee problems might stop their daily walking or jogging due to pain or fear of aggravating the problem. Such paitents might benefit from suggestions of low impact activities. Another common example are patients with sub-optimally managed asthma who might shy away from cardiorespiratory activities because of their shortness of breath.
Medications	Some medications can make patients intolerant to exercises as a side effect, like the widely used beta blockers. Also some other commonly used drugs are the blood thinners that may make patients avoid strenuous activities for the fear of causing bleeding.
Physical disability	Individuals with disability may have limited options of physical activities to adopt and may also require special supervision and equipment making it less convenient and more expensive.
Time availability	Individuals with restricted time availability may find it hard to meet even the minimum physical activity levels in a week.
Indoor exercise equipment	Availability of indoor exercise equipment has the potential to make involvement in physical activity more convenient.
Gym membership	This may indicate an individual's commitment to initiating or maintaining physical activity. It may also motivate one by way of peer support. However, cost, location proximity, and business hours may be some of the limitations.

Attribute	Significance
Sports	Most sports require moderate to high level of physical activity. Some of the downsides might be that they can be team dependant and some may require training and special facilities. Aged individuals may find it more difficult to adopt a new sport.
Friend availability	Involvement of friends may motivate an individual more.

The user is at liberty to answer as many questions as they prefer. The implications of this liberty comes at the expense of relevancy of suggestions. Given a complete user profile, the APKM would filter out more relevant suggestions for the user, on the other hand, given an incomplete user profile, the APKM filtered suggestions would be generic as well.

One might ask: *Why do users can only choose from a pre-selected list of values?* Admittedly this is a limitation of our current modeling approach because of practical reasons. As this thesis is aimed at providing a proof-of-concept for how knowledge-based modeling approaches be used for modeling life-style change interventions with potentially high chances of success owing to their behaviour-theoretic foundation, this was accepted as a reasonable trade-off in implementation.

5.2.3 Suggestion Modeling

The *suggestion model* is intended to filter the best APSs from APSR thus making it the heart of our APKM. It uses the user model to do so. By selecting APSs based on the user model, we are presenting APSs that are relevant to the user thus increasing their likelihood to be taken up by the user and turned into concrete action plans. By following through these action plans, the user is potentially increasing their chances of experiencing success and thus enhancing their sense of Self-Efficacy as a result of having that success experience.

Suggestion modeling formalized our implementation strategy as outlined in chapter 4 §4.3.2 as APKM. The series of steps involved were:

1. Identify and define the **concepts**.
2. Identify and define the **relationships** between concepts.
3. Identify and define **constraints** to be imposed upon these concepts and relationships.

5.2.3.1 Concepts

The name of each concept and its definition as intended to be used in our model is as follow.

User represents the individual.

Goal represents an individual's intention to work on a problem (barrier).

Barrier represents the problem that has been abstracted from the self-regulatory efficacy questionnaire.

APS represents Action Plan Suggestion in one-to-one correspondence as defined and described in chapter 4 §4.3.1. They represent all the possible candidates of suggestion for the *User*. All **APSs** must define their suitibality profile for every attribute and for every barrier. The concept APS along with all its instances actually represents the APSR.

Attribute represents a salient characteristic of the User that modifies the filtering of APSs in some meaningful manner. It is gathered as part of the user profile.

Value represents the possible states that an attribute can acquire. The values have a fixed codomain (range)—an intentional decision made in response to demonstrative and proof-of-concept concerns.

5.2.3.2 Relationships between Concepts

The identified concepts must be rendered with meaningful ties to each other for the APKM to answer its primary question. An pictorial overview of how concepts relate to each other is shown in Figure 5.3 and a detailed explanation follows.

A user can specify an attribute and, therefore, is related to the Attribute through *hasAttribute* relationship. An attribute further is related to some Value through *hasValue*

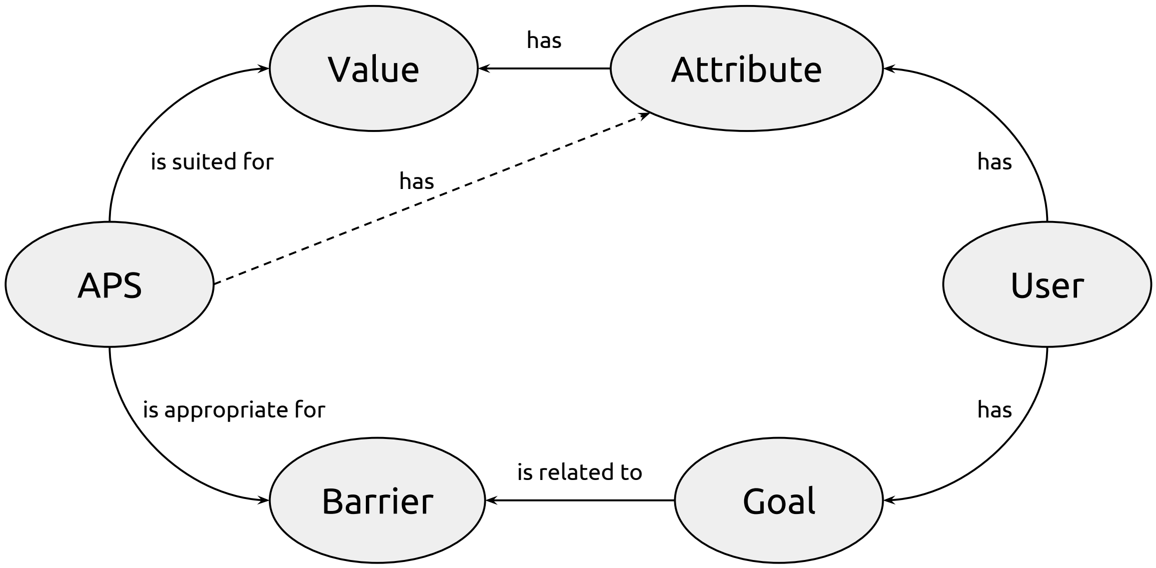

Figure 5.3: Relationships identified between Concepts.

relation. This trio of *User–Attribute–Value* actually represents a single user characteristic and a collection of them constitues the *user profile*.

A user also needs to specify a goal they intend to pursue. To model this requirement, the concept user is related to the concept goal through *hasGoal* relationship. Our definition of goal—the intention to overcome a specific barrier—necessitates some sort of relation between goal and a barrier. This necessity is reified in the model as *isRelatedTo* relation between a goal and a barrier.

Our conceptualization requires APSs to specify for which values of attributes and for which barriers they are most suitable for thus constituting *APS Attribute Profile* and *APS Barrier Profile* respectively. This lead us to introduce two more relations: *isSuitedForValue* and *isSuitedForBarrier* in our model. Quite evident from their names, the *isSuitedForValue* relation relates an APS to a value and *issuitedForBarrier* relation relates an APS to a barrier.

The conceptualized relationships along with their domains, codomains and inverses, and whether they are inferred are summarized for quick overview in Table 5.6.

Table 5.6: List of conceptualized relationships

Name of Relation	Domain	Codomain	Inverse Relation	Inferred
hasAttribute	User	Attribute	forUser	No
hasValue	Attribute	Value	forAttribute	No
hasGoal	User	Goal	goalForUser	No
isRelatedToBarrier	Goal	Barrier	isRelatedToGoal	No
isSuitedForValue	APS	Value	valueIsRelatedTo	No
isSuitedForBarrier	APS	Barrier	barrierIsRelatedTo	No
forUser	Attribute	User	hasAttribute	Yes
forAttribute	Value	Attribute	hasValue	Yes
goalForUser	Goal	User	hasGoal	Yes
isRelatedToGoal	Goal	Barrier	isRelatedToBarrier	Yes
valueIsRelatedTo	Value	APS	isSuitedForValue	Yes
barrierIsRelatedTo	Barrier	APS	isSuitedForBarrier	Yes

5.2.3.3 Constraints on Concepts and Relationships

A user can specify any number of profile attributes as they feel comfortable or none at all. Not specifying any attribute implies production of generic suggestions as a direct consequence of user characteristics not being taken into consideration in the APS filtering phase. In addition, in case a user can directly specifies a value, the user must be related to the attribute corresponding to that value through automatic inference.

- Attributes can be related to one or many values but a value is related to only one attribute. The values for attributes are pre-specified and are listed in Table 5.1.
- A user can only specify one goal at a time. Allowing selection of multiple goals simultaneously might lead to ambiguitiy in suggestions because suggestions are personalized in relation to goals as well. This constraint prevents possibility of such an event.
- Every possible goal that a user can pursue is in 1–1 correspondence with a barrier. The 1–1 cardinality constraint restricts one goal from embodying many barriers.

- An APS specifies **`isSuitedFor`** relation to some value of an attribute which constitutes the *APS attribute profile*. An APS can be asserted for all the values of a certain attribute. The relation between APS and Attribute will be automatically inferred.

- Similar to the APS Attribute Profile, an APS must be mapped to at least one barrier to constitute the *APS barrier profile*. An APS not mapped to any barrier is a candidate for removal. At the most, an APS can be related to many barriers and the converse holds true as well through automatic inference of the inverse relation. A single atomic APS can be valid for many barriers at the same time.

- Even though APS and goals have no direct relation to each other, through indirect relation of barriers to goals, APSs get related to the goals for which they are best suited for.

A concise graphical representation of the above description is shown in Figure 5.4. The dashed lines are the relations automatically inferred through existing assertions whereas the dotted arrows running in the opposite direction to solid arrows denote the inverse relationship between two concepts.

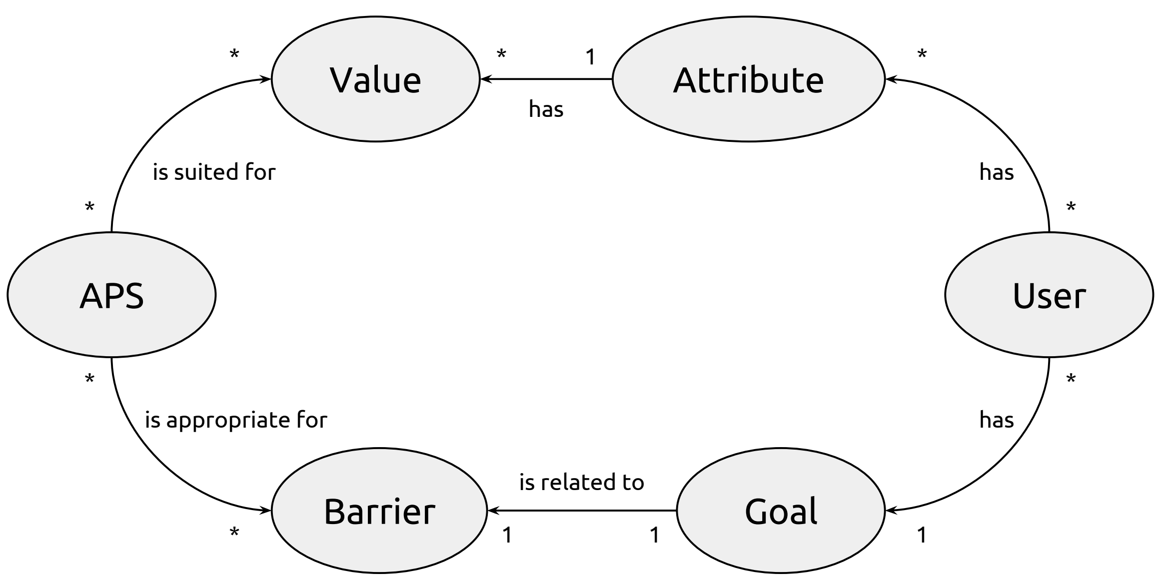

Figure 5.4: Constraints on Concepts and Relationships.

5.2.4 Section Summary

This section presented a detailed account of the second step of the implementation of APKM to address the core problem statement. We divided the discussion in two sections of User modeling and Suggestion modeling for convenience. User modeling presented the selection of user profile attributes which will help personalize suggestions. Suggestion modeling presented the identification of concepts, relationships and constraints of the APKM model. The output of this step was an APKM conceptual model ready to be translated into an ontological artefact.

5.3 Ontology Engineering

The ontology model is the actual physical model that is used to represent the conceptual model. We used Protege 4.5 to construct the APKM ontology out of the APKM conceptual model. We use the widely deployed (popular and web-friendly) OWL formalism to create physical artefact of our knowledge model. The steps are sequentially described in the the following sub-sections.

5.3.1 Translating APKM into OWL

A brief overview of translating APKM into OWL using Protege version 4.5 is detailed along with snapshopts below.

5.3.1.1 Classes

The concepts in the APKM knowledge model are directly translated as OWL classes. A snapshot of all the classes is shown in Figure 5.5 below.

Notice the existence of a class "*UserPlan*" not present in our conceptual model. It is a placeholder concept representing the best matched APSs for a certain User.

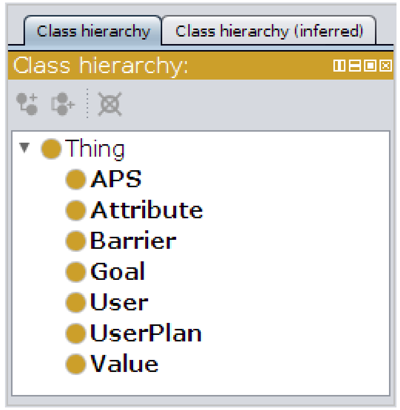

Figure 5.5: OWL Classes

5.3.1.2 Properties

OWL properties represent the relationships between classes. Every property has a domain and range (codomain). A property can be one of the two types, either a "data type" property or an "object type" property. The data type properties relate a class to a value space like numbers and strings. The object type properties relate a class to another class. They have classes both in their domain and range (codomain).

We followed the following naming convention for naming object properties for easy recognition of domain and range classes.

```
<concept>–<relationship>–<concept>  OR  <class>–<property>–<class>
```

The class on the left side indicating the domain of the object property and the class on the right indicating the range (codomain) of the property. For example, consider the property **`userHasAttribute`**. One can easily determine from the name that this property has the domain "User" and the range "Attribute".

Translating conceptualized relationships of the APKM model into an OWL model resulted in the emergence of the following properties. My modeling consists of only object properties. Every property along with their domain and codomain is listed.

Table 5.7: List of conceptualized relationships

Relation	OWL Property	Domain	Codomain	Inferred
hasAttribute	userHasAttribute	User	Attribute	No
hasValue	attributeHasValue	Attribute	Value	No
hasGoal	userHasGoal	User	Goal	No
isRelatedToBarrier	goalIsRelatedToBarrier	Goal	Barrier	No
isSuitedForValue	apsIsSuitedForValue	APS	Value	No
isSuitedForBarrier	apsIsSuitedForBarrier	APS	Barrier	No
forUser	attributeForUser	Attribute	User	Yes
forAttribute	valueForAttribute	Value	Attribute	Yes
goalForUser	goalForUser	Goal	User	Yes
isRelatedToGoal	barrierIsRelatedToGoal	Barrier	Goal	Yes
valueIsRelatedTo	valueIsRelatedToAPS	Value	APS	Yes
barrierIsRelatedTo	barrierIsRelatedToAPS	Barrier	APS	Yes

A snapshot from Protege 4.5 properties tab is shown in Figure 5.6.

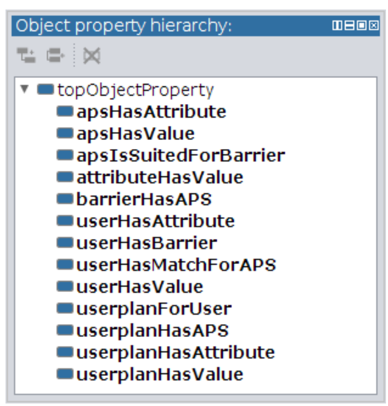

Figure 5.6: OWL relationships

5.3.1.3 OWL Axioms and SWRL Rules

OWL classes and properties can have associated *OWL axioms* and *SWRL rules* to either constrain the relationship or entail new relationships among existing concepts from among the pool of existing relationships. All the constraints imposed on the concepts and relationships in our APKM conceptualization were either translated to some OWL axiom or some SWRL rule. One of our aims was to reduce the number of manual assertions to be inserted by the user and infer as much relationships automatically as possible. Some of these OWL axioms help us achieve this goal. All the axioms and rules in our APKM ontology are shown in the Table 5.8.

Table 5.8: List of OWL axioms and SWRL rules

Type	Axiom / Rule
OWL	`apsHasValue ◦ inverse(attributeHasValue) → apsHasAttribute`
OWL	`inverse(barrierHasAPS) → apsIsSuitedForBarrier`
OWL	`inverse(apsIsSuitedForBarrier) → barrierHasAPS`
OWL	`userHasValue ◦ inverse(attributeHasValue) → userHasAttribute`

SWRL	`apsHasValue(?aps,?v) ∧ apsIsSuitedForBarrier(?aps,?b) ∧`
	`userHasBarrier(?u,?b) ∧ userHasValue(?u,?v) ∧`
	`userplanForUser(?up,?u) → userplanHasAPS(?up,?aps)`

Consider the following OWL axiom:

```
userHasValue ◦ inverse(attributeHasValue) → userHasAttribute
```

This particular OWL axiom is called a *property chain axiom* and is used to entail a new relationship between the domain class of the starting property and the range class of the last property in the chain. The ◦ is the *porperty chain operator* and can take an arbitrary number of properties as arguments. The chain is uni-directional and runs only in one direction.

The **`attributeHasValue`** property, in the above example, has the domain *Attribute* and range *Value*. The property emerging after the evaluation of **`inverse(attributeHasValue)`** will be the property having range of **`attributeHasValue`** as its domain and the domain as its range. Inverse of any property is another property with the domain and range of the original property flipped.

This particular OWL axiom can be graphically represented as shown in Figure 5.7.

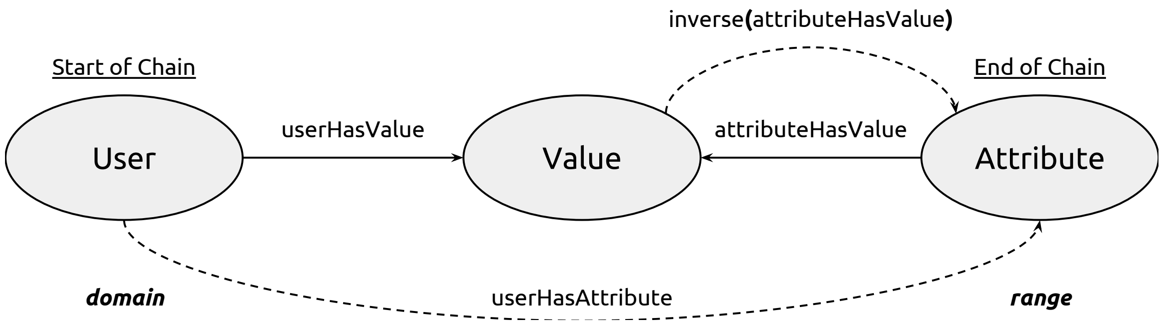

Figure 5.7: An example showing how property chain axiom works

This axiom infers the relationship between user and attribute if the user has an assertion for some value and that particular value is related to some attribute.

Similarly, consider the following SWRL rule. The intent of this SWRL rule is to find the APSs that are suitable for a given APS and are asserted by the user and assert them for the UserPlan class.

```
apsHasValue(?aps,?v) ∧ apsIsSuitedForBarrier(?aps,?b) ∧
userHasBarrier(?u,?b) ∧ userHasValue(?u,?v) ∧ userplanForUser(?up,?u)
→ userplanHasAPS(?up,?aps)
```

The part of the rule to the left of the arrow is the *antecedent* (body of the rule) and the part on the right is the *consequent* (head of the rule). The antecedent consists of multiple *atoms* delimited by the logical conjunction operator (∧). The consequent is evaluated to either **`true`** or **`false`** and is true if the antecedent holds—meaning all the atoms in the antecedent evaluate to true.

Given the above rule, the atom **`apsHasValue(?aps,?v)`** evaluates to true if there exists an asserted property **`apsHasValue`** between some APS—denoted as **`?aps`**—and some Value—denoted as **`?v`**—in the instantiated ontology. In the same vein, all other atoms are evaluated to either true or false. The consequent can only be true if all atoms in the antecedent evaluate to true because they are joined by logical conjunction.

To make it more concrete, suppose we have an APS "walk to work", a Value "young age", a Barrier "I am often feeling too tired", a User "John" and a UserPlan "User

Plan For John". Both **`apsIsSuitedForBarrier(?aps,?b)`** and **`apsHasValue(?aps,?v)`** will evaluate to true if the following relationships exist in the instantiated ontology.

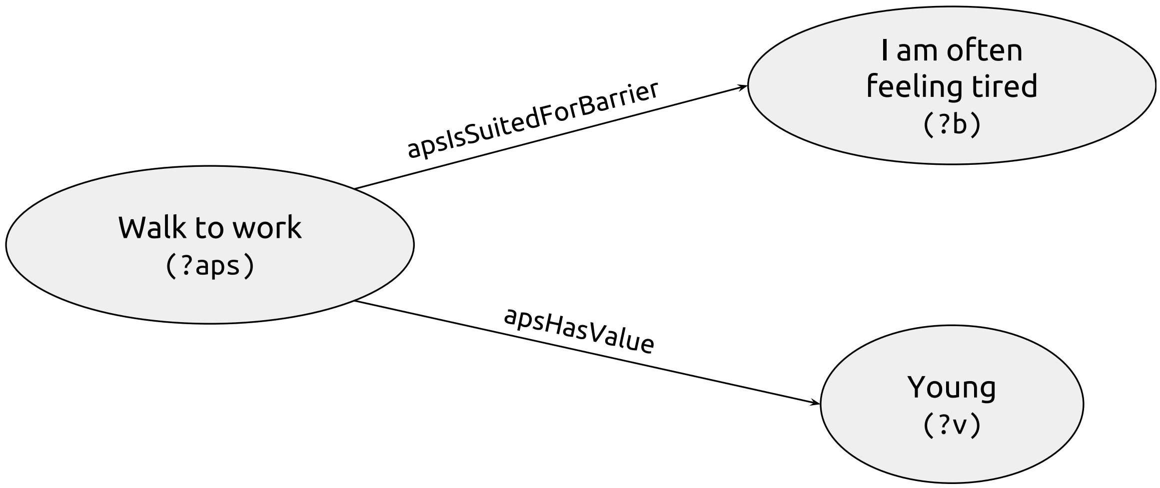

Figure 5.8: Diagrammatic representation of SWRL rule (#1)

Similarly **`userHasBarrier(?u,?b)`** and **`userHasValue(?u,?v)`** will evaluate to true if the following relationships exist in the instantiated ontology.

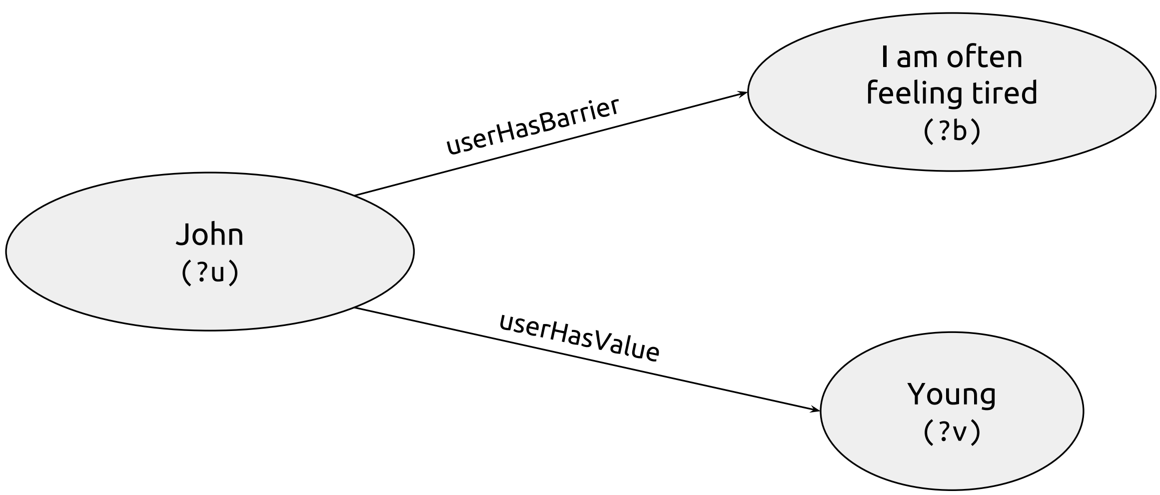

Figure 5.9: Diagrammatic representation of SWRL rule (#2)

The **`userplanForUser(?up,?u)`** relation must also hold true for the given user as it is the class which will hold the inferred APSs.

If the above three situations hold in the instantiated ontology, then the consequent would evaluate to true resulting in entailement of **`userplanHasAPS(?up,?aps)`** relationship between the UserPlan and the APS.

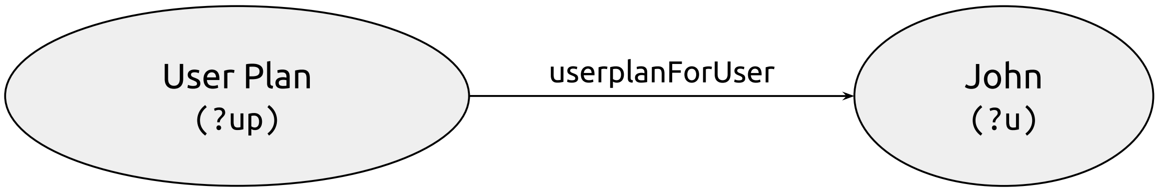

Figure 5.10: Diagrammatic representation of SWRL rule (#3)

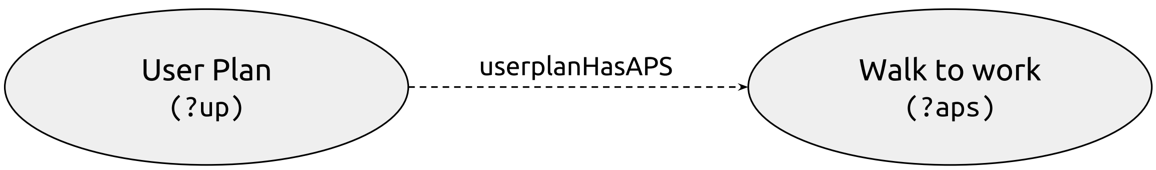

Figure 5.11: Diagrammatic representation of SWRL rule (#4)

An edited snapshot from Protege 4.5 where all the OWL axioms and SWRL rules are put together is shown in Figure 5.12. In the "Rules" window, the comma represents a logical conjunction (∧).

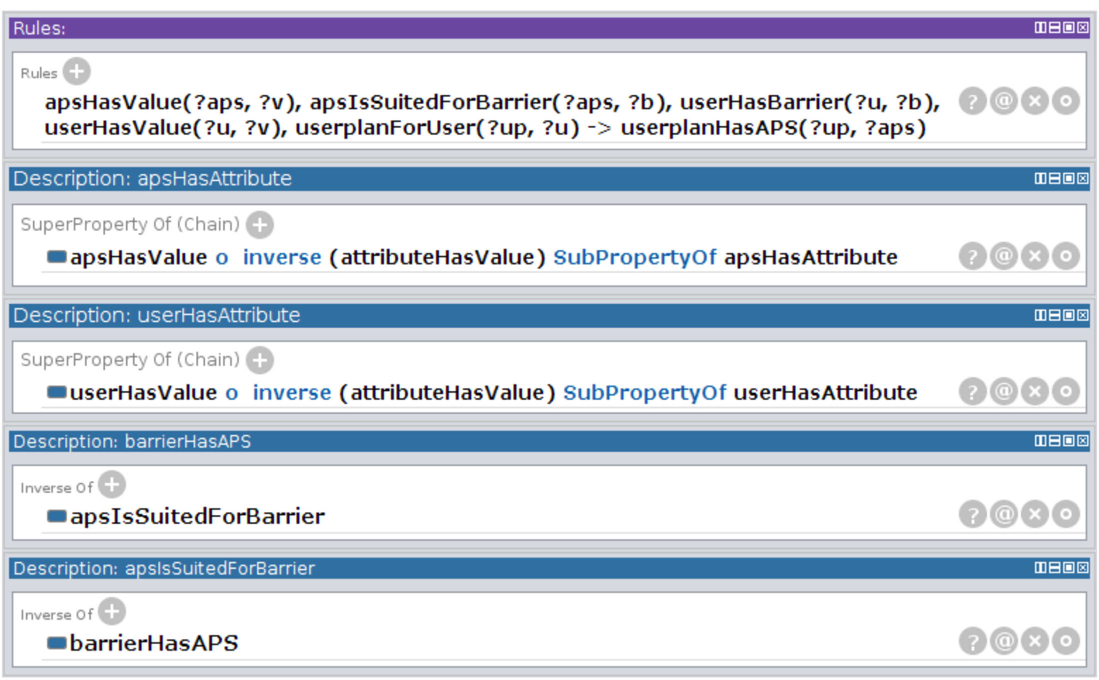

Figure 5.12: OWL axioms and SWRL rules

5.3.2 Section Summary

In this last section, we presented details of translating the conceptual APKM model into an ontological artefact using OWL as the knowledge representation language.. The translation was mostly faithful to the conceptual APKM model with only slight additions or modifications in the OWL artefact.

5.4 Concluding Remarks

This chapter presented the implementation details of the APM in three distinct phases. The first section discussed our content gathering strategy that was used to gather content for constructing APSR and SREQR—the content backbone of APKM. The second section discussed the formation of APKM conceptual model in terms of *user modeling* and *suggestion modeling*. The third and the last section discussed step-by-step construction of an ontological artefact from the APKM conceptual model using OWL as the language of choice for knowledge representation. In the next chapter, we will instantiate the ontological artefact using representative case scenarios and use them in scenario-based testing which is our primary means of evaluating the constructed OWL model.

CHAPTER 6 EVALUATION

This chapter presents the fourth step—*evaluating the APKM ontology*—in our research methodology to ensure the validity of the knowledge model. We assess the construction of our APKM ontology on the grounds whether it correctly implements the ontology requirements and answers the competency questions set forth in the design phase [92]. To this end, we devised two evaluation strategies to ensure that our APKM ontology has adequate representational adequacy and it functions as intended. Following a brief discussion on different ways to approach ontology evaluation, we will present the evaluation criteria selected to evaluate our APKM ontology with details in the subsequent sections.

6.1 Evaluation Approaches

There are a number of criteria to evaluate ontologies, and often contradictory in nature [81]. An ontology may perform well when evaluated based on one set of criteria as compared to a different set of criteria. Further, the selection of these criteria is partly dictated by the *purpose* and *scope* of the ontology. These inherent trade-offs call for a careful selection of evaluation criteria for any given ontology [81].

Before laying out our criteria for evaluation of APKM ontology, it is important to highlight the subtle differences between *ontology validation* and *verification*. Gómez-Pérez introduced these terms to formalize the two orthogonal aspects of ontology evaluation [81]. In short, *ontology validation* refers to modeling the world correctly i.e. ensuring correspondence between definitions of ontology and the intended perception of the reality to be modeled. It is the harder aspect of ontology evaluation because it requires human domain expertise and, therefore, does not lend itself well to automation [81]. *Ontology verification*, on the other hand, refers to building the ontology in the correct manner i.e. ensuring no error crept in while constructing the ontology. Of these two, ontology validation is the only way to ensure *correctness* of the knowledge encoded within [81].

Of all the ontology evaluation criteria given in [81], [82], [93], we selected the following criteria for evaluating our APKM ontology knowledge model:

1. Scenario-based Evaluation
2. Qualitative Evaluation
    i. Completeness
    ii. Consistency
    iii. Conciseness

A descriptive account of each follows in the following sections.

6.2 Scenario-based Evaluation

Evaluation based on specific scenarios is one of the ways to assess the ontology [82], [93]. The intent of scenario-based evaluation is to assess whether the APKM produces the desired output or not. The three main steps in the process are:

1. Instantiating the APKM Ontology
    i. Defining the *user profile*
    ii. Defining the *APS barrier profile*
    iii. Defining the *APS attribute profile*
2. Setting up result expectations
3. Reporting the results

Each step is elaborated in the proceeding sub-sections.

6.2.1 Instantiating the APKM Ontology

Instantiating the APKM ontology consists of defining three profiles: the user profile, the APS barrier profile, and the APS attribute profile.

6.2.1.1 Defining the User Profile

Total of four case profiles **A**, **B**, **C**, and **D** were prepared which correspond to *scenarios* in scenario-based evaluation. For convenience, they were pseudonymed **John**, **Jane**, **Alice**, and **Mary** respectively. All these case profiles were representative of the condition of actual patients requiring self-management and were prepared in consultation with a medical graduate. Two of them were 80% similar in terms of attribute values while the other two had 80% disparity. Table 6.1 shows all the constructed case profiles. When defining user profiles, some preliminary conditions that must be respected are:

1. For attributes **medical condition** and **medications**, the value must always be **none**.
2. For a user, only one barrier can be asserted at one time. Asserting multiple barriers at one time will result in undesired intermingling of APSs.
3. APSs for two user profiles, whether similar or dissimilar, are comparable only when asserted barriers for both are the same.

Table 6.1: Case profiles with 80% similarity and disparity

	80% Similar		80% Dissimilar	
Profile Attribute	John	Jane	Alice	Mary
Age	Young	Old	Adult	Adult
Gender	Male	Female	Female	Female
Residence	CityCenter	Rural	City	City
Profession	Full-time	Home-maker	Full-time	Home-maker
BMI	Overweight	Underweight	Normal	Normal
Medical Conditions	None	None	None	None
Medications	None	None	None	None
Physical Disability	No	No	No	No
Time Availability	Less	High	Low	High
Indoor Equipment	Yes	No	Yes	Yes
Gym Membership	Yes	No	Yes	Yes
Sports	Moderate	Low	Low	Low
Friend Available	Yes	No	Yes	Yes

In addition to populating the user profile, we also need to create corresponding **UserPlan** instances for each user. A userplan instance acts as a placeholder for the best matched APSs for a specific user.

6.2.1.2 Defining APS Barrier Profile

Every barrier has some relation with an APS. This relationship characterizes which APS is suitable for which barrier. Later it will be exploited for inferential purposes when defining rules and axioms for personalizing APSs. One can assert as many barriers as a particular APS seems suitable for. For evaluation purposes, we selected the following two barriers:

1. I cannot go out due to bad weather
2. I have too much workload

Table 6.2 lists all the asserted APSs for these two barriers. For the sake of brevity, the barrier **`I cannot go out due to bad weather`** is abbreviated as $\mathbf{B_1}$ and the barrier **`I have too much workload`** as $\mathbf{B_2}$ in Table 6.2 and onwards.

Table 6.2: APS barrier profile

APS	$\mathbf{B_1}$	$\mathbf{B_2}$
`aps_take_stairs_instead_of_elevator`	✓	✓
`aps_exercise_while_you_watch_tv`	✓	✓
`aps_walk_during_phone_calls`	✓	✓
`aps_do_the_dishes`	✓	
`aps_iron_clothes`	✓	
`aps_drive_to_local_shopping_mall_and_walk`	✓	
`aps_walk_inside_apartment_building`	✓	
`aps_brainstorm_project_ideas_while_walking`		✓
`aps_dont_use_drive_up_window`		✓
`aps_get_off_the_bus_one_stop_earlier`		✓
`aps_park_far_away_from_destination`		✓
`aps_take_a_brisk_walk_during_lunch_break`		✓

APS	B_1	B_2
aps_walk_around_office_building_during_break		✓
aps_walk_while_waiting_for_plane_at_airport		✓

6.2.1.3 Defining APS Attribute Profile

Our conceptualization also relates APSs to profile attributes in terms of their suitability. Again this relationship is exploited through rules and axioms when filtering suitable APSs for an individual given their profile attributes. This constitutes the APS attribute profile. Only those attributes are specified for which the APSs should match. Two APSs along with their attribute profiles are shown in Table 6.3. See Appendix C for a list of all APS attribute profiles specified for this evaluation.

Table 6.3: Examples of two APS attribute profiles

Profile Attribute	Walk inside Apartment Building	Drive to Shopping Mall and Walk
Age	Adult, Old	Adult
Residence	City	City, CityCenter
Profession	Student, Home-maker	Full-time
Physical Disability		No
Time Availability	Moderate, High	Low, Moderate
Friend Availability		Yes

6.2.2 Setting up Expectations

Lastly, *expectations* define the desired output and meaningful conclusions we can draw from our ontology given all of the above profiles. We grouped our expectations as *reasoner-specific expectations* and *content-specific expectations*.

6.2.2.1 Reasoner-specific expectations

These are ontology-wide expectations independent of the specific configuration of the *user profile* or *APS attribute profile*. These kind of expectation assess the inherent connections of the APKM ontology and should always be fulfilled. Table 6.4 lists all of our reasoner-specific expectations that we expect to meet. The letter "**R**" subscripted with a number corresponds to a specific reasoner-specific expectation .

Table 6.4: Reasoner-specific expectations

No.	Expectation
R_1	For all Userplans A, B, C, and D, at least one `userplanHasAPS` property should be inferred
R_2	APSs with undefined *APS Barrier Profile* should not appear in any Userplan
R_3	APSs with undefined *APS Attribute Profile* should not appear in any Userplan
R_4	Userplan for Users with no barriers should not infer `userplanHasAPS` property
R_5	Userplan for Users with no attributes should not infer `userplanHasAPS` property
R_6	Userplan for Users with no values should not infer `userplanHasAPS` property
R_7	Users only with asserted values should infer `userHasAttribute` property
R_8	UserPlan with no assertion for `userplanForUser` should not infer any `userplanHasAPS` property
R_9	For every Barrier, `barrierHasAPS` should be inferred given the assertion `apsISSuitedForBarrier` for APS

6.2.2.2 Content-specific expectations

Content-specific expectations pertain to the specific *APSs* indicating whether they should be inferred or not based on the given configuration of the *User* and *APS* profiles. These are the only meaningfully assertions that can be made for an APS content-wise.

The evaluation will constitute two rounds differentiated based on the specific barrier being asserted for the User. In round one, content-specific assertions would pertain to the barrier B_1 i.e. *I cannot go out due to bad weather*. Table 6.5 lists all the content-specific expectations that must hold in round one of the evaluation after running the reasoner.

Table 6.5: Content-specific expectations for barrier B_1

No.	Expectation	For UserPlans
C_1B_1	`aps_take_stairs_instead_of_elevator` should be inferred	A, B, C
C_2B_1	`aps_walk_during_phone_calls` should be inferred	A, C, D
C_3B_1	`aps_drive_to_local_shopping_mall_and_walk` should be inferred	A, C, D
C_4B_1	`aps_walk_inside_apartment_building` should be inferred	B, C, D
C_5B_1	`aps_do_the_dishes` should be inferred	B, D
C_6B_1	`aps_iron_clothes` should be inferred	B, D

In the second round, content-specific assertions would pertain to the barrier B_2 i.e. *I have too much workload*. Table 6.6 outlines all the content-specific expectations that must be met in the second round of the evaluation.

Table 6.6: Content-specific expectations for barrier B_2

No.	Expectation	For UserPlans
C_1B_2	`aps_brainstorm_project_ideas_while_walking` should be inferred	A, C

No.	Expectation	For UserPlans
C_2B_2	*aps_take_stairs_instead_of_elevator* should be inferred	A, B, C
C_3B_2	*aps_dont_use_drive_up_window* should be inferred	A, C
C_4B_2	*aps_walk_during_phone_calls* should be inferred	A, B, C, D
C_5B_2	*aps_park_far_away_from_destination* should be inferred	A, C, D
C_6B_2	*aps_walk_while_waiting_for_plane_at_airport* should be inferred	A, C
C_7B_2	*aps_get_off_the_bus_one_stop_earlier* should be inferred	A, B, C, D
C_8B_2	*aps_take_a_brisk_walk_during_lunch_break* should be inferred	A, C
C_9B_2	*aps_walk_around_office_building_during_break* should be inferred	A, C
$C_{10}B_2$	*aps_exercise_while_you_watch_tv* should be inferred	B, D

6.2.3 Evaluating and Reporting the Results

We run the Pellet reasoner to entail the inferences. The best APSs for each user are inferred for their corresponding userplan instances and are are shown in Tables 6.7 and 6.8 for the first and second round of evaluation respectively.

Table 6.7: APSs matched in round one

APS	A	B	C	D
aps_take_stairs_instead_of_elevator	✓	✓	✓	
aps_exercise_while_you_watch_tv		✓		✓
aps_walk_during_phone_calls	✓	✓	✓	✓

APS	A	B	C	D
aps_do_the_dishes		✓		✓
aps_iron_clothes		✓		✓
aps_drive_to_local_shopping_mall_and_walk	✓	✓	✓	✓
aps_walk_inside_apartment_building		✓	✓	✓

Table 6.8: APSs matched in round two

APS	A	B	C	D
aps_take_stairs_instead_of_elevator	✓	✓	✓	
aps_exercise_while_you_watch_tv		✓		✓
aps_walk_during_phone_calls	✓	✓	✓	✓
aps_brainstorm_project_ideas_while_walking	✓		✓	
aps_dont_use_drive_up_window	✓		✓	
aps_get_off_the_bus_one_stop_earlier	✓	✓	✓	✓
aps_park_far_away_from_destination	✓		✓	✓
aps_take_a_brisk_walk_during_lunch_break	✓		✓	
aps_walk_around_office_building_during_break	✓		✓	
aps_walk_while_waiting_for_plane_at_airport	✓		✓	

The actual outcomes of both evalaution rounds are summarized against expected outcomes in Table 6.9.

Table 6.9: Overall results

Expected Outcome	Round 1 Actual Outcomes	Round 2 Actual Outcomes
R_1	✓	✓
R_2	✓	✓
R_3	✓	✓
R_4	✓	✓
R_5	✓	✓
R_6	✓	✓

Expected Outcome	Round 1 Actual Outcomes	Round 2 Actual Outcomes
R_7	✓	✓
R_8	✓	✓
R_9	✓	✓
C_1B_1	✓	NA
C_2B_1	✓	NA
C_3B_1	✓	NA
C_4B_1	✓	NA
C_5B_1	✓	NA
C_6B_1	✓	NA
C_1B_2	NA	✓
C_2B_2	NA	✓
C_3B_2	NA	✓
C_4B_2	NA	✓
C_5B_2	NA	✓
C_6B_2	NA	✓
C_7B_2	NA	✓
C_8B_2	NA	✓
C_9B_2	NA	✓
$C_{10}B_2$	NA	✓

Given the above results, **precision** will be defined as *the fraction of actual outcomes that meet our specified expectations* and is given by the formula:

$$Precision = \frac{ActualOutcomes \cap ExpectedOutcomes}{ActualOutcomes \cup ExpectedOutcomes} \tag{6.1}$$

For first round of the evaluation, precision is calculated to be:

$$Precision = \frac{15}{15} = 100\% \tag{6.2}$$

and for the second round:

$$Precision = \frac{19}{19} = 100\% \tag{6.3}$$

Because the system is deterministic in nature. the results reported above in terms of precision are not astounding.

6.3 Qualitative Evaluation

Vrandečić in [81], [93] summarized the ontology quality criteria based on an extensive literature review. For qualitative evaluation of our APKM ontology, we leveraged his existing work and short-listed the following qualitative evaluation criteria: *completeness*, *consistency*, and *conciseness*.

6.3.1 Completeness

One should note that *no model is ever complete*. In order to assess completeness of the model, we need to define completeness in a way that is measureable. Grüninger and Fox proposed formal and informal competency questions as a way to capture the questions the ontology should be able to answer [93], [94]. Competency questions are set forth prior to ontology development [82] and serve to capture the knowledge in the domain as questions to be answered by the ontology model. From the perspective of Grüninger and Fox, then *completeness* is defined as the state of the ontology when it can answer all the competency questions set forth initially i.e. fulfil all the competencies [93], [95]. Hence, competency questions not only guide the ontology construction but they become a means to evalute completeness of the ontology afterwards. The knowledge that is expected to be in the ontology should either be explicitly asserted or be inferrrable through a reasoner [93].

APKM ontology is focused on answering only one competency question: *What APSs are best for a Person given his Barrier?* Completeness, in our case, corresponds more to completeness with regards to the application requirements set forth by the competency question [93] and is best demonstrated after instantiation. Scenario-based evaluation in the previous section demonstrated that our APKM ontology is able to answer the competency question. Based on these results, we claim that our APKM ontology is *complete* because all the concepts, relationships, axioms, and rules required to answer the competency question are appropriately represented.

6.3.2 Consistency

First and foremost, consistency or coherence refers to the absence of *asserted* or *inferred* contradictory statements within the ontology [92], [94]. Inconsistency renders classes in the ontology with an *empty intension* [81], [96] and thus no model is able to satisfy the ontology axioms leaving it in an unusable state [81]. Inconsistencies can either be logical or non-logical in nature. Logical inconsistencies arise due to conflicting axioms and are detectable by reasoners whereas non-logical inconsistencies arise due to semantic conflict between concept definitions and their usage in axioms. To illustrate non-logical inconsistency, consider a term "Jaguar" defined as "a feral cat living in the jungle" and have an associated relationship stating "Jaguar is a Car" [93]. An ontology is regarded as *consistent* if there exists neither *asserted* nor *inferred* contradictions of either logical or non-logical nature per se [92]. Logical consistency can easily be established by running the reasoner. Non-logical consistency is harder to determine through software agents or automated means and requires human expertise. We used the Pellet and Snorocket reasoner to check the consistency and satisfiability of our APKM ontology. The results of running the reasoner indicated that there are no conflicting axioms or rules and contradictions cannot be inferred [93]. This established the *logical consistency* of our APKM ontology. Because APKM ontology is logically consistent, there exists at least one model that satisfies the axioms of the ontology, thus rendering it *satisfiable* as well.

Secondly, it refers to harmony between the formal description (specification) and informal description (documentation) of the ontology. In the APKM ontology, informal descriptions of the onotlogy are hosted inside annotations as comments under their respective entities. All the formal statements in APKM ontology are in line with their informal natural language descriptions i.e. the comments that document the APKM ontology match the intended definitions of OWL concepts [93].

Thirdly, it refers to the absence of unusual representation choices made for the ease of implementation [97]. In our APKM ontology, some representation choices may be made purely for concerns of implementation [97]. An example would be reifying the attributes as a concept instead of representing them as data properties of the **`User`** concept to facilitate evaluation of axioms and rules to find the best matched APSs for a User. Despite some unusual representation choices, the logical and non-logical consistency of the APKM ontology remains preserved.

6.3.3 Conciseness

An ontology is considered *concise* if it contains no irrelevant or unnecessary definitions; no redundant definitions; and redundancies cannot be inferred from asserted definitions [92], [93]. Again we used the Pellet and Snorocket reasoners to establish the absence of irrelevant definitions and redundancies. The results of running the reasoner indicated that our APKM ontology does not include any irrelevant concepts or axioms with regards to the domain to be covered and the competency question to be answered [93], [94]. An example of an irrelevant axiom would be an axiom about *university's accounts department* in our APKM ontology. Also no redundant concepts or axioms [93] were found.

6.4 Concluding Remarks

This chapter presented an account of the APKM ontology evaluation. We discussed scenario-based evaluation by instantiating the ontology, defining the required user and various APKM profiles, and finally running and reporting the results. We also carried out the qualitative evaluation wherein focus was concerted on *completeness*, *consistency*, and *conciseness* of the APKM ontology. Various evaluations were promising with respect to the aims we set forth upfront in the design phase.

CHAPTER 7 DISCUSSION

This chapter summarizes the key findings of our research, documents certain limitations of our solution approach, and highlights further avenues to explore and new research questions to ask in the light of the current work.

7.1 Revisiting the Problem Statement and Research Objectives

Chronic conditions are long-standing conditions and require day-to-day management. The modern age has seen a steady rise in chronic illnesses that is projected to increase further in times to come. This indicates the need for effective preventative and management strategies for chronic illnesses. Among those strategies are *lifestyle interventions* which are essentially behavior change interventions concerned with promoting adoption of healthful behaviors as well as curbing the harmful ones.

Healthful behavior adoption and maintenance is intrinsically a complex phenomenon by nature. The *inertia* to initiate the behavior change process and later maintain *regularity* in performing a given healthful behavior presents a seemingly insurmountable challenge. Most behavior change interventions focus on educating and counseling the patients. Solely focusing on educating patients about health risks and benefits does not guarantee a subsequent change in behavior. Further, physicians are found to be unable to counsel the patients about behavior change either due to *lack of time* or *training* [8].

To meet the above-mentioned challenge, we devised our solution approach taking a healthcare knowledge management perspective. To this end, a knowledge-driven self-management intervention having a behavior theoretic foundation to prevent and manage chronic illnesses was proposed. The challenge was to demonstrate that knowledge-driven systems can be used to potentially deliver a behavior-focused self-management intervention for managing chronic illness. The primary objective of this thesis was to present a proof of concept system demonstrating the possible use of knowledge engineering techniques in the making of a system to deliver an SCT-based intervention in the physical activity domain using a Self-Efficacy enhancing approach. The primary objective was pursued in the hope to meet the larger objective of enabling chronic disease patients to improve their lifestyle based on proven behavior change determinants. The ultimate aim was to demonstrate that *behavior change theory* based knowledge-driven model has the potential to generate personalized self-management plans for chronic disease patients.

7.2 Summary of our Solution Approach

Our solution approach was premised on the finding that Self-Efficacy plays a central role in the behavior change process, so techniques and methods that enhance an individual's Self-Efficacy are an effective way to promote and sustain behavior change. A comprehensive self-management system, well-grounded in SCT principles, conforming to Bandura's self-regulatory system principles was proposed which combined *proactive guidance* with *reactive adjustments* [25]. Proactive guidance in terms of helping one in setting a goal and constructing an action plan, thus establishing the standard to compare one's weekly performance against. Reactive guidance in terms of feedback about weekly performance to evaluate progress and appraise performance in relation to the set goal. The cognitive appraisal of performance against a standard—the *action plan* in our case—serves to provide individuals the necessary information that enhances or lessens their sense of efficacy.

Of the four sources of efficacy information, first-hand experience of successful performance is evidently the most influential source for raising Self-Efficacy of an individual [27], [28], [88]. This *success* experience, no matter how trivial, has been proven to enhance self-efficacy. Hence, we took a *performance-oriented* approach to enhancing self-regulatory efficacy in individuals. Our strategy utilized *goal-setting* and *action planning* techniques to drive successful performance of activities [3]. Consequently we emphasized *action plans* because they provide an opportunity to the individual to gain *success* experience through engagement in performance which is theorized to increase Self-Efficacy of the individual over time. Our strategy was geared towards enhancing individual's Self-Efficacy over time by promoting successive success experiences to overcome the barriers to some behavior by helping to create achievable action plans.

Our self-management system was conceptualized to have four modules corresponding to Bandura's *core determinants* of human behavior. Of the four module, the design and implementation of *Action Planning Module (APM)* was the focus of this thesis. APM implemented the *goal-setting* and *action planning* techniques to drive successful performance of activities [3]. The materialized Action Planning Module (APM) consisted of a *Process* and some *Content*, and an APKM that consumed the Content and informed the process. A schematic diagram of Action Planning Module (APM) is shown in the Figure 7.1 below.

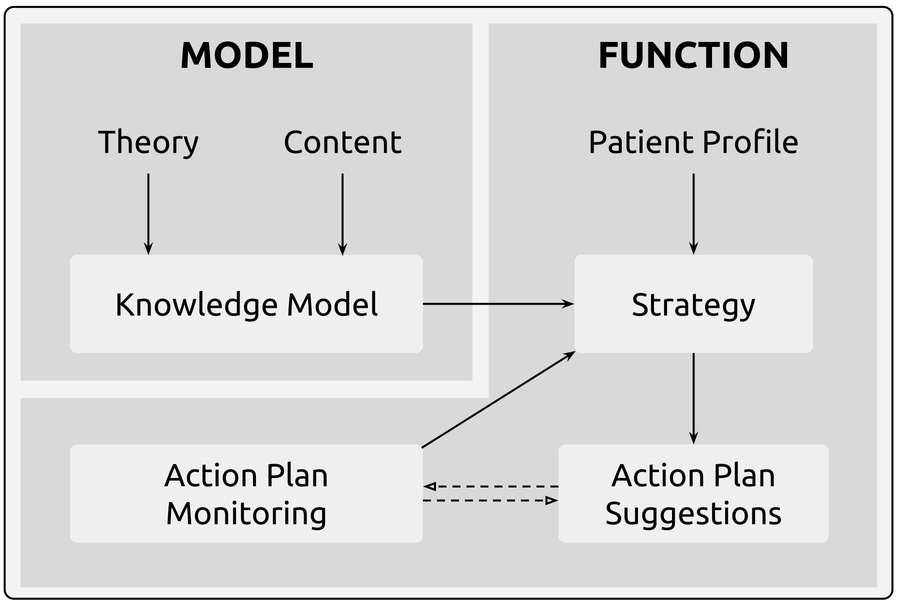

Figure 7.1: Action Planning Module

To summarize, this thesis demonstrated the applicability of knowledge-engineering approach in designing knowledge-based self-management systems. A three-step knowledge engineering approach was used consisting of steps: *content gathering*, *conceptual modeling*, and *ontological modeling*. The salient phases of the implementation consisted of the **designing and development of the APKM Ontology** and subsequent **instantiation of it with relevant content**. The APKM ontology was designed to *intelligently* answer the question *What APS is best for a Person given his Barriers?* given the user profile, APS barrier profile, and APS attribute profile. Moreover, we used a *suggestion-based approach* to help individuals overcome *barriers*. That lead us to formalize two content repositories namely ***APSR*** and ***SREQR*** where APSR housed *suggestions* to overcome commonly encountered barriers to the physical activity performance and SREQR housed all the Self-Regulatory Efficacy Questionnaires to act as source of barriers to the performance of physical activity. For a complete description of our methodology and implementation, the reader is referred back to chapter 3 and 4.

7.3 Possible Real World Application

Our model in it's current state may not be usable by chronically ill patients on a routine basis. However, this current formulation has the potential to be used by healthcare providers in assisting such patients in identifying barriers to performance of any behavior under consideration. This assistance from healthcare providers would help such patients in the selection and use of APSs as intended in this conceptualization. This is an alternate way of fulfilling the objective of this thesis— building a resilient sense of self-efficacy—by assisting patients in setting them on the path to lifestyle change in the long run by helping them overcome barriers to performance of any behavior.

Furthermore, healthcare providers can also act as domain experts in vetting APSs before being considered by the patients. This step would help ensure presentation of clinically safe and significant APSs to the patient further increasing their likelihood of positively affecting their sense of Self-Efficacy by potentially increasing the chances of APSs being taken up by chronically ill patients and their later conversion into action plans.

7.4 Limitations of our Current Solution Approach

The prime objective of this thesis was to demonstrate the *applicability* of knowledge engineering approach to engineering behavior-focused self-management interventions. Various decisions made to achieve this objective gave rise to some methodological and operational limitations that are enumerated below in no order of significance:

1. The SCT foundation is one of the biggest strengths of our approach but is also one of the biggest limitations. This implies that our framework is tightly bound to the SCT-based world view which might be a limitation in some cases. Future work should explore the possibility of a theory-agnostic framework.

2. Our solution strategy primarily utilizes a Self-Efficacy enhancing approach within the larger context of SCT. Of the four ways to enhance self-efficacy, our approach encourages the use of *mastery experience* which is undoubtedly the most effective of all of them. Enhancing Self-Efficacy requires cognitive appraisal of the performance. This theoretical commitment to SCT has the downstream effect that because self-improvement is hinged on the cognitive appraisal of performance and experience of success, it means that chronic conditions in which cognitive function is diminished are not a good candidate for such an intervention [98]. A very common example would be stroke patients left with a very limited sensorimotor ability. They would benefit little from this approach because they are unable to appraise their performance cognitively to be meaningful enough in raising their Self-Efficacy levels.
3. Reactive guidance is one of the hallmarks of a self-regulatory system as described by Bandura and is usually in terms of feedback about weekly performance to evaluate progress and appraise performance in relation to the set goal. Meeting that requirement, in our context, translates to defining a way to incorporate user feedback back into our process model. Right now there is no specified way to incorporate feedback into the system.
4. The current version of our APKM implementation assumes that the process described in our research methodology (chapter four) holds true all the time. The embedded and hard-wired process is opaque to future changes and, therefore, makes this approach a non-resilient one. A superior and much better way will be to make the process model *explicit* and defining a way to hook knowledge into the explicit process. Future work should explore the possibility of making the process explicit in the APM implementation.
5. In this implementation, we randomly and arbitrarily chose some barriers to physical activity and then collected APSs for them. A better way would have been to look at systematic reviews to find out the most common barriers to physical activity and then collect *action plan suggestions* for them.

6. In our APM process model, we are limiting APSs to a preselected list of built-in suggestions. Future work should explore the possibility to incorporate open-ended suggestions and a way to reconcile user-solicited suggestions with the pre-existing and built-in ones.
7. The codomain (range) of values in user attributes is closed which is a potential limitation. An open-ended range would allow the possibility to add more values if and when necessary. The conceptual handling of an open-ended codomain might require some remodeling at our end but this possibility should definitely be explored for future relevancy of the current model.

7.5 Possible Future Directions for Extending the Work

Our current proof of concept implementation can be extended in the following ways:

1. Grouping APSs based on some common criteria and categorizing APSs based on efficacy level and strength. In order for Action plans to positively influence an individual's SE, we need to promote successful execution of activity and so they are designed to be achievable/attainable. Self-Efficacy of an individual determines how much effort individuals will put in to perform an activity. Failure to perform the activity for an individual having a low sense of Self-Efficacy will negatively affect their self-efficacy. Classifying the APs according to efficacy/level and strength helps us avoid getting into this situation.

2. This suggestion presumes the implementation of previous suggestion of categorizing APSs. One possible direction for incorporating user feedback can be to keep track of which APS worked for a person with a specific configuration of a user profile. Then there are three ways this information can be used by our knowledge model.

    1. The likelihood of giving that suggestion to a person with more or less the same user profile configuration is lowered but not entirely eliminated.
    2. Other APSs in the same category are either more or less likely to be suggested. This means that if one specific APS didn't work for a person, then APSs in the same category are less likely to be suggested in future.

3. Integration of APKM model with social network activity of the user can be explored in the context of how the suggestion of a particular APS will be affected by the social connections and influences.

7.6 Conclusion

This thesis presented a proof of concept system demonstrating that a knowledge-based behavioral preventative and management strategies for chronic illnesses can be modeled and would presumably be more effective owing to having a strong theoretical foundation. It is well-established that biomedical approaches alone are insufficient for holistic management of chronic illnesses and the emergence of *Lifestyle Medicine* and *Behavioral Medicine* in the last decade is a testament to this increasingly evident phenomenon. There has always been a need for an effective way to personalize and deliver such behavioral interventions. In this context, we proposed and then—through this thesis—demonstrated that behavioral interventions can be delivered using a knowledge-based system that is designed to personalize the experience of behavior change for individual patients. The value of such knowledge-driven systems is twofold: *they require minimal clinician input* and *they can personalize the behavior change program for the individual on the fly*.

To reiterate our research contributions, this thesis demonstrated:

1. **Conceptualization of a behavior theory based self-management framework:** The behavior-theoretic foundation is derived from Bandura's seminal work on Social Cognitive Theory spanned over decades in establishing empirical evidence for it. Our self-management framework hosts self-management aspects as modular functional components. Semantics of various modules have been defined and implementations may vary in number as long as they adhere to the predefined semantics.

2. **Proof-of-Concept Knowledge-based Implementation of APM:** This thesis also demonstrated the applicability of knowledge-engineering approach in designing knowledge-based self-management systems. A three-step knowledge engineering approach was used consisting of steps: *content gathering*, *conceptual modeling*,

and *ontological modeling*. The implementation further comprised of the following steps worthy of mention under research contributions:

i) **Development of APKM Ontology:** APKM ontology was designed to *intelligently* answer the question *What APS is best for a Person given his Barriers?* given the user profile, APS barrier profile, and APS attribute profile. It can be considered the heart of the APM.

ii) **Populating APKM Ontology with Relevant Content:** We used a *suggestion-based approach* to help individuals overcome *barriers*. That lead us to formalize two content repositories namely ***APSR*** and ***SREQR*** where APSR housed *suggestions* to overcome commonly encountered barriers to the physical activity performance and SREQR housed all the Self-Regulatory Efficacy Questionnaires to act as source of barriers to the performance of physical activity.

Knowledge-driven personalized behavior interventions for chronic illness management and prevention is just a humble start. The projected rise of chronic diseases in the next decades will put enormous burden on global and Canadian economy as well as Health Delivery Services. This push will ultimately incentivize home-based interventions and approaches with minimal clinician input for life-long prevention and management of chronic diseases as a direct response to reducing the burden on country's economy and health service delivery organizations.

With these challenges on our horizon, knowledge-driven behavior change interventions emerges to be a promising potential solution to support chronically ill patient population in their homes, therefore, not only improving the quality of life for patients but also saving the time of clinicians and nurses as well as economizing the delivery of health services within the country.

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APPENDIX A LIST OF ACTION PLAN SUGGESTIONS

No.	Action Plan Suggestion
1	Try a morning dose of exercise
2	Take a brisk walk during lunch break
3	Park far away from destination
4	Walk/bike to work
5	Walk to shopping mall
6	Skate to shopping mall
7	Walk the dog
8	Exercise while you watch TV
9	Skate to work
10	Watch TV while pedaling a stationary bicycle
11	Put a jump rope in suitcase and jump rope
12	Walk the halls and climb the stairs in hotels.
13	Visit the local shopping mall and walk for half an hour or more. (Mall Walking)
14	Trade babysitting time with a friend, neighbor, or family member who also has small children.
15	Try to exercise when the kids are at school
16	Try to exercise when the kids are sleeping
17	Get off the bus one stop earlier
18	Walk during business calls (when you don't need to reference important documents OR Stand up and move around while making phone calls.)
19	Do your own yard work
20	Mow the lawn with a push mower
21	Plant and care for a vegetable or flower garden
22	Don't use the drive-up window.

No.	Action Plan Suggestion
23	Don't stay seated for more than 30 minutes
24	Push baby in stroller
25	Clean the house
26	Wash the Car
27	Play with kids
28	Iron your clothes
29	Walk with your children
30	Replace a coffee break with a brisk 10-minute walk. Ask a friend to go with you.
31	Join the office softball team or walking group.
32	Brainstorm project ideas with a coworker while taking a walk. (Walking Meeting)
33	Walk down the hall to speak with someone rather than using the telephone.
34	Get off a few floors early and take the stairs the rest of the way.
35	Walk while waiting for the plane at the airport.
36	Stay at hotels with fitness centers or swimming pools and use them while on business trips.
37	Walk around your building for a break during the work day or during lunch.
38	Use a stand-up desk.
39	When golfing, walk instead of using a cart.
40	Jump rope
41	Take stairs instead of elevator at workplace
42	Take stairs instead of elevator at apartment building
43	Do the dishes
44	Do housework yourself instead of hiring someone else to do it.
45	When you drop family at the shopping mall, do Mall Walking
46	Ride your bike to work / shopping

No.	Action Plan Suggestion
47	Organize school activities around physical activity
48	Select activities requiring minimal time, such as walking, jogging, or stairclimbing.
49	Consider Inviting a friend/family member to walk/exercise with you OR Invite a friend to exercise with you on a regular basis and write it on both your calendars.
50	Consider planning a social activity involving exercise

APPENDIX B SELF-REGULATORY SELF-EFFICACY QUESTIONNAIRE

Self-Efficacy to Regulate Exercise

A number of situations are described below that can make it hard to stick to an exercise routine. Please rate in each of the blanks in the column how certain you are that you can get yourself to perform your exercise routine regularly (three or more times a week).

Rate your degree of confidence by recording a number from 0 to 100 using the scale given below:

0	10	20	30	40	50	60	70	80	90	100
Cannot do at all					Moderately can do					Highly certain can do

	Confidence (0-100)
When I am feeling tired	_____
When I am feeling under pressure from work	_____
During bad weather	_____
After recovering from an injury that caused me to stop exercising	_____
During or after experiencing personal problems	_____
When I am feeling depressed	_____
When I am feeling anxious	_____
After recovering from an illness that caused me to stop exercising	_____
When I feel physical discomfort when I exercise	_____
After a vacation	_____
When I have too much work to do at home	_____
When visitors are present	_____
When there are other interesting things to do	_____
If I don t reach my exercise goals	_____
Without support from my family or friends	_____
During a vacation	_____
When I have other time commitments	_____
After experiencing family problems	_____

APPENDIX C LIST OF APS ATTRIBUTE PROFILES

Table C.1: Do the dishes

Consideration	Value
Residence Location	Rural
Profession	Unemployed, Home-maker
Time Availability	High
Indoor Exercise Equipment	No
Gym Membership	No
Friend Available for Exercise	No

Table C.2: Drive to Shopping Mall and Walk

Consideration	Value
Age	Adult
Residence Location	City, CityCenter
Profession	Full-time
Physical Disability	No
Time Availability	Low, Moderate
Friend Available for Exercise	Yes

Table C.3: Iron Clothes

Consideration	Value
Age	Old
Profession	Home-maker
Physical Disability	Yes
Time Availability	High

Consideration	Value
Friend Available for Exercise	No

Table C.4: Walk during Phone Calls

Consideration	Value
Age	Adult
Profession	Full-time
Time Availability	Low

Table C.5: Walk inside Apartment Building

Consideration	Value
Age	Adult, Old
Residence Location	City
Profession	Student, Home-maker
Time Availability	Moderate, High

Table C.6: Take Stairs instead of Elevator

Consideration	Value
Time Availability	Low
Indoor Exercise Equipment	No
Friend Available for Exercise	No

Table C.7: Walk during Phone Calls

Consideration	Value
Age	Adult, Old
Profession	Full-time

Consideration	Value
Time Availability	Low

Table C.8: Brainstorm project ideas while working

Consideration	Value
Residence Location	CityCenter
Profession	Full-time
Time Availability	Low

Table C.9: Don't use drive up window

Consideration	Value
Residence Location	CityCenter
Profession	Full-time
Time Availability	Low

Table C.10: Exercise while you watch TV

Consideration	Value
Profession	Student, Home-maker
Time Availability	Moderate, High
Indoor Exercise Equipment	No
Gym Membership	No

Table C.11: Get off bus one stop earlier

Consideration	Value
Residence Location	City, CityCenter
Profession	Student, Home-maker

Consideration	Value
Time Availability	Low

Table C.12: Park far away from destination

Consideration	Value
Residence Location	City, CityCenter
Profession	Full-time
Time Availability	Low

Table C.13: Take a brisk walk during lunch break

Consideration	Value
Profession	Full-time
Time Availability	Low

Table C.14: Walk around the office building during break

Consideration	Value
Profession	Full-time
Time Availability	Moderate, Low

Table C.15: Walk while waiting for plane at the airport

Consideration	Value
Profession	Full-time
Time Availability	Low