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ABSTRACT

The acquisition of expertise involves the adoption of a between-systems problem-solving approach. A between-systems problem-solving approach involves (1) category restructuring; (2) analogy formation; and (3) solution construction using symmetrical and asymmetrical mapping information. Category restructuring permits the expert to reframe the initial problem state. Reframing the problem leads to the formation of analogical functional and complementary connections between category members. The identification of symmetrical and asymmetrical mappings determines the extent to which information from an analogous system can be borrowed with or without modification, and subsequently incorporated into a problem solution. (Contains 25 references and 2 figures.) (Author)

A STRATEGY FOR THE ACQUISITION OF PROBLEM-SOLVING EXPERTISE IN HUMANS: A SYSTEMS APPROACH.

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RUNNING HEAD: Acquisition of Expertise

The acquisition of expertise involves the adoption of a between-systems problem-solving approach. A between-systems problem-solving approach involves (1) category re-structuring (2) analogy formation and (3) solution construction using symmetrical and asymmetrical mapping information. Category re-structuring permits the expert to re-frame the initial problem state. Re-framing the problem leads to the formation of analogical functional and complementary connections between category members. The identification of symmetrical and asymmetrical mappings determines the extent to which information from an analogous system can be borrowed with or without modification, and subsequently incorporated into a problem solution.

The development of expertise in a given domain involves three fundamental processes: (1) the ability to de-construct and reconstruct categories (2) the ability to form analogical connections between concepts derived from such categories and (3) the ability to use analogical connection information in asymmetrical and symmetrical mapping formation. First and foremost, problem-solving expertise is predicated on the categorization of critical concepts derived from the initial problem domain. The manner of categorization constrains the search for relevant, parallel information, information that is potentially useful in solution generation.

De-construction and Reconstruction of Categories

Unlike the novice, the expert can restructure a given category in order to re-frame the initial problem state. The expert perceives and represents the category as a dynamic entity, rather than a static entity. Lockhart, Lamon, and Gick (1988) found that novices experienced problem difficulty because they failed to re-conceptualize a given problem. Lockhart et al. (1988) found that once appropriate reconception was achieved, such re-conception assisted novices in information transfer between relevant domains. The transfer of information between relevant domains promoted the solving of simple insight problems. Experts, who solved similar insight problems, were more facile with the re-conceptualization

process and experienced less difficulty in the problem-solving task. Hence, experts demonstrated more flexible problem representations than novices, and these flexible representations promoted more effective problem resolution.

The expert can deconstruct a given category into its component members and can reconstruct the category using different feature, property, or relation criteria in order to determine membership. Chi, Feltovich, and Glaser (1981) found that novice physics students sorted mechanics problems exclusively in terms of superficial features, such as problem wording overlap or mechanical device utilized. Experts sorted mechanics problems according to abstract principles of operation. Similar differences in flexible category representation were found for experts in both the domains of text-editing and computer programming (Kay & Black, 1985). Schoenfeld and Hermann (1982) found that problem perception and representation changed through the learning procedure. Schoenfeld and Hermann (1982) studied the classification of mathematical problems before and after students took a course on mathematical problem-solving. Prior to the course, students sorted problems on the basis of objects described in the problem. As mathematical expertise increased, the students sorted problems by methods required to negotiate the problem or mathematical principles illustrated in the problem. Several researchers have found that induction of an abstract category occurs when subjects are directed

to compare analogous problems (Bassok & Holyoak, 1990; Gick & Holyoak, 1983; Novick & Holyoak, 1991). Based on these category abstraction results, Cummins postulated that comparing problems would cause novices to abstract the causal problem features that define expert category membership. In a related study, Cummins found that analogical comparison facilitated classification of problem structures, whereas individual sorting tasks caused subjects to categorize based on surface resemblances. Taken together, this evidence indicates that expert categories are biased toward structural, unifying information whereas novice categories are biased toward contextual or situational information.

Because expert categories consist of deep, structural representations which are more resistant to change, flexible category representation can occur without disrupting the core identity of the category. Hence, experts can possess more than one representation for a given category. For example, the expert can represent the category 'economy' in one of many different ways. The category 'economy', when discussed in relation to macroeconomic theory, includes capitalist, socialist, and communist members. A member of the 'economy' category is an economic system that is organized around a set of economic principles in a governmental context. The category 'economy', when discussed in relation to token economies and behavioral modification strategies, contains members that are differentiated according to

reinforcement schedules. Hence, token economies utilize reinforcement schedule criteria for membership. Examples of members in a token economy would include: continuous reinforcement, fixed ratio-three chores, and fixed interval-one hour schedules.

In contrast to the novice, the expert represents categories as consisting of a core set of invariant principles and a variable member-specific, cluster-specific, or domain-specific component set. The core principles consist of extracted commonalities which are preserved in the category re-structuring. The category 'economy', both in reference to macroeconomic theory and token economy practice, refers to the manner in which goods and services are produced, distributed, and consumed. Certain economic principles, such as the Law of Diminishing Productivity and the Law of Diminishing Utility, characterize all economic systems. Such global principles constitute the category foundation. The variable category information is specific to a particular member, member cluster, or domain. During wartime, governments resort to direct control over production and over the extension and conversion of production facilities. Since states of war are unique to countries and nation-states, wartime economic policy applies only to political economies and not to token economies.

Consequently, the expert is able to re-frame the initial problem state by category re-structuring. Category re-structuring entails

increasing category size and category scope through the following means: (1) inclusion of lower-typicality members so that the final category membership contains a broad range of typicality values and (2) varying the level of abstraction of category members where abstraction is defined as the availability and use of perceptual detail for concept understanding. The initial representation of the category 'economy' can be expressed in the following manner:

Economy: {communist, socialist, capitalist, mixed}
(1) smaller category size
(2) members are characterized by relatively uniform typicality and abstraction measures.

One can represent the re-structured category as follows:
Economy: {communist, socialist, capitalist, mixed, organismic, household, theological, token, multinational}
(1) larger category size
(2) members possess diverse typicality and abstraction measures.

Insert Figure 1 about here

Functional, Complementary, and Analogical Connections

The restructuring of a given category influences the nature of connections that are formed between categories and between the concepts that are derived from categories. The human expert, unlike the human novice, forms several types of connections between category and concept information. While the novice forms predominantly functional connections between concepts, the expert forms functional connections, complementary connections, and analogical connections. Functional connections specify the operation of a particular structure within a given system. For example, the category 'economy', when referring to token economy, includes the functional relation between social approval, tokens, and positive reinforcement. One can represent functional information causally, as well. Social approval induces the distribution of positive reinforcement in the form of tokens. Hence, tokens function as an indicator of social approval.

Complementary connections are properties, features, or relations that co-occur within a given system. In Euclidean geometry, angles that are complementary co-occur or correlate with one another. In essence, complementary connections are those connections that have high correlativity measures. In a token economy, the reduction of tokens is correlated with improved socialization skills. The improvement in socialization skills is correlated with the nature of the treatment plan and the patient's discharge date. This

complementary connection specifies the relation between reinforcer withdrawal, presence of socially-acceptable behavior, and discharge date. A token economy is implemented in an institutional setting. An institutional setting has certain high probability features and properties that co-occur. The property of structured treatment activities co-occurs with the features of patient evaluation records and medical personnel.

Analogical connections represent complementary and functional connections between two or more systems that share a form of abstract similarity. Paper money and tokens constitute an analogical functional relation; each serves to provide purchasing power for goods and services. In both political and token economies, time-allocation and labor-allocation decisions are made by governmental structures and individual workers. Time-allocation and labor-allocation decisions are inherent properties of both political and token economies. Time-allocation and labor-allocation decisions serve as an example of analogical complementary connections, which use property information. An example of analogical complementary relations includes the correlation measures between savings and resource level, found in both token and political economies. Consequently, individuals with less resources will save a greater percentage of their resources but a lesser absolute amount of those resources.

Several studies document the importance of analogical complementary and functional connections in analogical problem-solving tasks. Holyoak, Junn, and Bellman (1984) reported that surface dissimilarity impaired the retrieval of salient analogs in children. Gentner and Landers (1985) found that surface similarity disruption influenced the access of relevant analogs in adults, who needed relevant analogs for problem-solving tasks. Finally, Holyoak & Koh (1987) found that surface and structural similarities influenced the mapping of correspondence information, as well as the retrieval of analog information. Hence, co-occurrence and functional connections are important in analog retrieval and correspondence mapping.

The use of analogical connections constitutes the principle output of a divergent thinking approach, or a systems problem-solving approach. A systems problem-solving approach searches for the solution to a given problem outside the domain from which the initial problem state is derived. Collins and Gentner (1986) found that experts often searched between domains in order to access relevant explanatory analogies. Furthermore, the same participant often invoked several models within a given domain to explain a process, such as the process of evaporation. Clement (1988) reported that the protocols of advanced physics graduate students revealed a heavy reliance on within and between-domain analogies. In the Clement study, experts generated analogical models through a

process of transformation. Experts found that the process of transformation was instrumental in negotiating impasses during the problem-solving process (Clement, 1988).

Analogical Connections and Mapping Information

A systems approach utilizes analogical connections in determining whether mappings between systems components and relations are asymmetrical or symmetrical (Alma, 1993). The purpose of characterizing mappings as symmetrical or asymmetrical is to determine the degree of correspondence between analogical connections. A symmetrical mapping occurs between analogical connections that possess a high degree of similarity, or a proximate 1:1 correspondence. The Law of Diminishing Utility, which specifies the relation between supply, production, and incentive, is characteristic of both political and token economic systems. Hence, a 1:1 mapping exists between political and token economies with respect to the Law of Diminishing Utility. An asymmetrical mapping exists between analogical connections that are not in a proximate 1:1 correspondence. In a political economy, the government influences fiscal and monetary policy by instituting tariffs and taxes. Although token economies are influenced by monetary policies such as wage setting and price setting, taxes and tariffs do not constitute a manner in which monetary policy is influenced within the token economy. Hence, political and token economies are asymmetric

with respect to monetary policies; only certain monetary policies are common to both economies.

A given system pair possesses a symmetrical: asymmetrical ratio, which denotes the proportion of symmetrical correspondences to asymmetrical correspondences. The correspondences that contribute to the ratio are derived from the analogical connections between the two or more systems. The human expert possesses a broad knowledge-base, and utilizes this broad knowledge-base to estimate the symmetric index, the asymmetric index, and the resultant ratio. The human expert analyzes the analogical connections between the political economy and the token economy, and constructs a solution based on the extent to which relevant entities correspond. When the amount of problem-specific symmetrical information is greater than the amount of problem-specific asymmetrical information, the expert borrows information, and substitutes relevant details. Major modification of borrowed information does not occur when the amount of symmetrical information is greater than the amount of asymmetrical information. When the amount of asymmetrical information is greater, the expert borrows information and modifies such information. After the borrowed information is modified, it is integrated with select pieces of information from the problem domain. The purpose of such integration is to construct a problem solution which is a synthesis of information from both systems.

Central to possessing expertise is the ability to (1) select the relevant entities from the systems in question and (2) combine the relevant entities into a cohesive solution.

Mapping Information and Problem-Solving: A Case Study

A learner can view problem-solving as category restructuring, analogical connection formation, and construction of a solution based on symmetrical and asymmetrical mapping information. A political economist interested in the production incentive problem of post-WW II communist economies would re-structure the category 'economy' to include token economy as well as political, theological, and organismic economies. The expert would then evaluate which economy category members could provide novel information about a communist economy. The expert can then re-frame the problem in terms of a token economy. The central question the expert would ask is whether one could learn about political economies from an analysis of token economies and/or other types of economies. A related question is whether the solution to the political economy problem can be found through an understanding of the token economy system, or through the integration of political economy and token economy system components and relations.

The expert would construct analogical connections between money-monetary incentive and token-reinforcement schedule. The asymmetrical mapping between monetary incentive and reinforcement schedule would permit the expert to note that reinforcement schedule differs from monetary incentive in its mechanism of operation. Nevertheless, the asymmetrical mapping, which is an analogical construct, would permit the expert to understand the communist economy in terms of a reinforcement schedule, where reinforcement would be contingent upon a low rate of responding per unit time. Hence, a solution to the problem of production incentive in a communist system could be constructed in terms of a differential rate of low responding schedule (DRL). In this instance, the problem solution is derived by forming an asymmetrical mapping between relevant system components and by borrowing the relevant component or relation from the system that is outside the problem domain.

A more complex political economic problem could address the issue of high production rates prior to a production deadline. Using the production rate problem, the expert draws the correspondence between economic rewards and public honors. Economic rewards and public honors are often bestowed upon the worker who meets production goals. An asymmetrical mapping can be formed between the worker who receives public honors and the patient who receives social approval after completing a requisite number of chores. The

expert can then re-frame the problem in terms of chained reinforcement schedules needed to produce certain work patterns. The expert postulates that during the time of production deadlines the laborer operates on a fixed interval schedule. On a fixed interval schedule, laborers slow down the rate of responding after a production deadline has passed. Thereafter, the worker reverts back to a DRL schedule, where increase in response rate acts to prevent reinforcement. The expert addresses the issue of differential productivity by combining explanations based on two reinforcement schedules, or system components. The expert continues to study patient behavior prior and subsequent to social approval in order to further understand production rate and worker output prior and subsequent to production deadlines. This integration of information explains the more complex phenomenon of differential worker productivity. Hence, after mapping formation, the expert borrows relevant information from each system in question. The expert constructs a solution using (1) information from both domains and (2) a higher-order combinatorial problem-solving schema which specifies "how to integrate information". This selective borrowing of system relations and components results in the integration of different system components in solution construction.

Model Predictions:

A strategy for inducing a systems problem-solving approach would entail directing the novice to the following activities:

(1) Acquisition of a multidomain knowledge-base with a paucity of connections between the domains. The novice must acquire such a knowledge-base and must be directed to utilize this knowledge-base in problem solving activities.

(2) Acquisition of category re-structuring practices. Category re-structuring would entail inclusion of members with a broad range of typicality and abstraction values. Category re-structuring would lead to a more flexible category representations. A more flexible category would facilitate shifting between category representations, depending on the context of the problem.

(3) Flexible category representation would extend to the complementary and functional connections which characterize the concepts derived from each category representation.

(4) Initially, analogical connections would have to be explicitly specified to the novice. After learning how to form and encode analogical connections, the novice would become more facile at forming these connections. With increasing expertise, the novice would start to form analogical connections between multiple pairs of category members instead of one pair of category members.

(5) Organization and re-structuring of a hierarchically-based category invariant consisting of extracted commonalities and associated complementary/functional connections. This category invariant would be continuously updated to accord with new information about a new economy 'x'. In other words, the novice would construct a higher order 'economy' schema. This 'economy' schema would contain the commonalities of all economies and would be derived from pre-existing domain-specific information. As expertise increased, this higher order schema would be updated. Updating would consist of adding and/or subtracting so that the 'economy' invariant would contain properties, features, and relations common to all economies. Hence, the category invariant is a dynamic one.

(6) With the acquisition of expertise, the novice would begin to utilize both asymmetrical and symmetrical mappings in problem-solving tasks. The novice-expert shift would entail less reliance on proximate 1:1 correspondences, or symmetrical mappings, and a greater reliance on asymmetrical mappings.

(7) With increasing expertise, the novice would rely less on the unmodified transfer of information from one domain to another. Problem-solving would entail the use of partial analogies between multiple domain pairs. Select, relevant information would be borrowed from each system pair and integrated into a problem solution.

Insert Figure 2 about here

Conclusion

In summary, the expert re-structures a given category in order to increase category scope and permit a greater number of options for re-framing the initial problem state. The re-framing of the initial problem state is conducive to the formation of analogical connections between category members. The expert problem-solver identifies symmetrical and asymmetrical mapping information in an attempt to determine the extent of correspondence between two or more category members. Expert problem-solving is predicated on utilizing a systems problem-solving approach. A systems approach entails borrowing the relevant information from an analogous system or, more commonly, integrating select pieces of information from both systems in the construction of a problem solution.

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Figure Captions

Figure 1. Initial and re-structured representations for sample categories.

Figure 2. Utilization of an analogy-based strategy for a systems problem-solving approach.

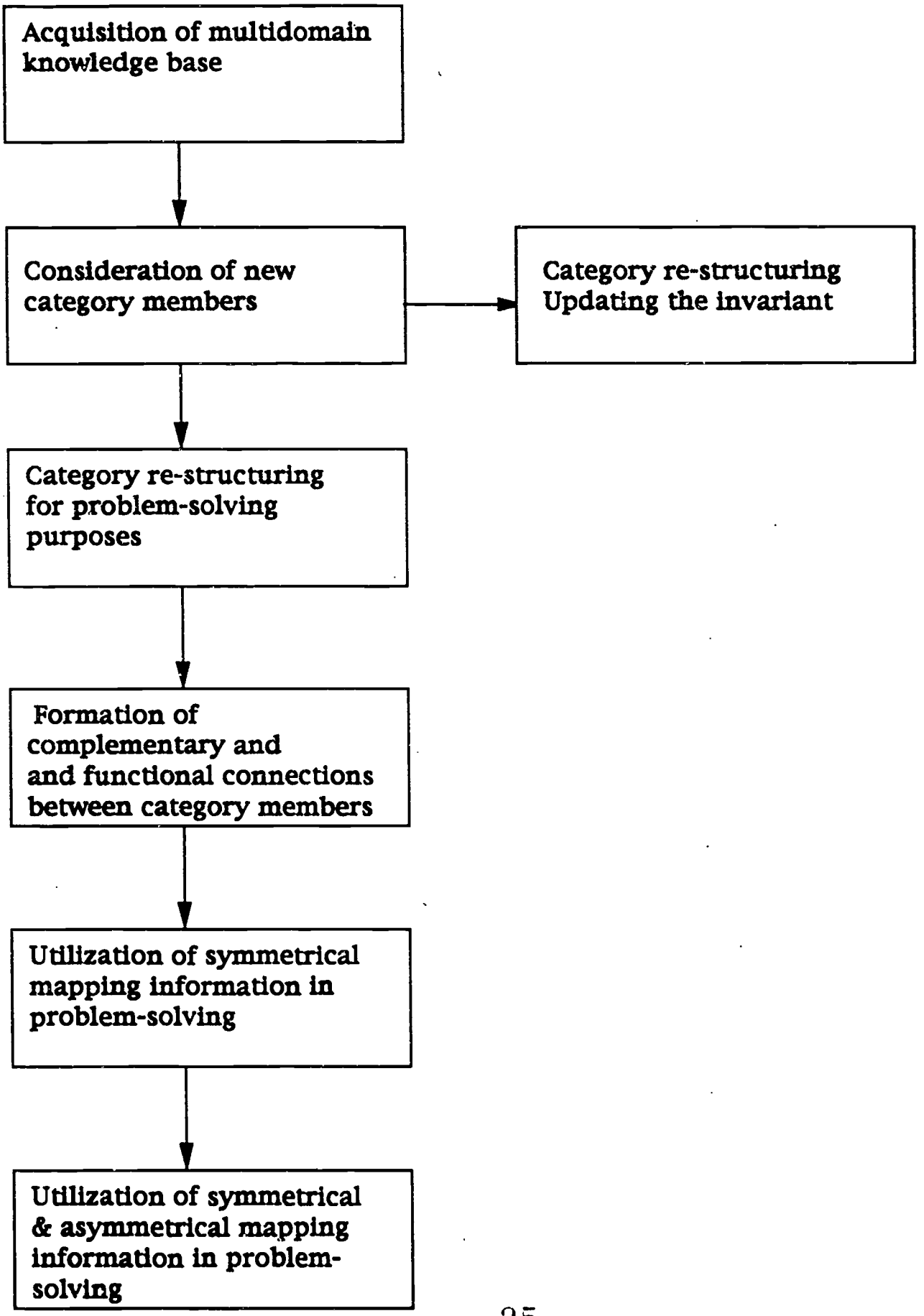
Category: *Economies*
Initial: {communist, socialist, capitalist, mixed}
Re-structured: {communist, socialist, capitalist, mixed, household, theological, token, multinational}

Category: *Diffusible Agents*
Initial: {electrolytes, nutrients, hormones}
Re-structured: {electrolytes, nutrients, hormones, auxins, environmental toxins, economic products, cultural ideas and practices, gene pools of immigrating/emigrating populations}

Category: *Judgment Errors*
Initial: {TAU-Regrettable Mistake, TAU-Red-Handed, TAU-Too-Late}
Re-structured: {TAU-Regrettable Mistake, TAU-Red-Handed, TAU-Too-Late, TAU-Post-Hoc, TAU-Unsupported Plan, TAU-Red-Herring}

Category: *Colonial Establishments*
Initial: {Colonial America 1492-1776, Greek colonialism 750-500 B.C., Roman colonialism 27 B.C.-305 A.D.}
Re-structured: {Colonial America 1492-1776, Greek colonialism 750-500 B.C., Roman colonialism 27 B.C.-305 A.D., Phoenician colonization 10th c. B.C., French colonialization of Western Africa 1830-1912, T'ang Dynasty colonialization 618-907 A.D.}

Category: *Childhood Diseases*
Initial: {Chicken pox, Common Cold, Measles}
Re-structured: {Chicken pox, Common Cold, Measles, Hydrocephaly, Immunodeficiency disease, Parasitic disease, Genetic disease}


Acquisition of multidomain knowledge base
Consideration of new category members
Category re-structuring Updating the invariant
Category re-structuring for problem-solving purposes
Formation of complementary and and functional connections between category members
Utilization of symmetrical mapping information in problem-solving
Utilization of symmetrical & asymmetrical mapping information in problem-solving