The Role of Analogical Abduction in Skill Acquisition

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Abstract. We discuss the effectiveness of analogical abduction in skill acquisition. Abductive inference makes it possible to find missing links that explain a given knack in achieving a skillful task. We introduced meta level abduction to realize rule abduction which is mandatory in finding intermediate missing links to be added in knack explanation. Analogical abduction can be achieved by adding analogical inference rules to causality meta rules within meta level abduction. We have applied our analogical abduction method to the problem of explaining the difficult cello playing techniques of spiccato and rapid cross strings of the bow movement. Our method has constructed persuasive analogical explanations about how to play them. We have used a model of forced vibration mechanics as the analogy base world for spiccato, and the specification of the skeletal structure of the hand as the basis for the cross string bowing technique. We also have applied analogical abduction to show the effectiveness of a metaphorical expression of "eating pancake on the sly" to achieve forte-piano dynamics, and successfully identified an analogical explanation of how it works. Through these examples, we show the effectiveness of analogical abduction in skill acquisition. Furthermore we discuss the importance of meta level representation as a basis for providing rich human cognitive paradigm such as causality, analogy and metaphor.

Keywords: rule abduction, analogical abduction, predicate invention, predicate identification, cello playing

1. Introduction

In acquiring skills in such activities as sports, playing instruments, drawing picture and so on, it is essential to get some sort of "knack" to perform those activities. The notion of achieving a knack refers to some kind of unexplained but necessary skill component, without which performance is lacking. In acquiring professional skill, it is said that we need continuous daily training or practice something like 10,000 hours. However it is very hard to spend such long period of time for ordinary people, like amateur athletes or musicians. For those people, the key strategy is to acquire some critical knack for achieving those skills. There are many possibilities in acquiring a knack, e.g., observing professionals' performance, being taught by trainers, conducting trial and error by themselves and so on. Such training methods have two important features in their processes; encountering a knack and assimilating and/or accommodating the knack. Trainers' suggestions are quite useful to encounter key points which play essential roles in understanding the knack. Observation of professionals' performance sometimes makes it possible to acquire an ideal form of performance which may give a solution for achieving the given task. Trial and error is useful to finding key points to realize the task and to get the knack by themselves. It is always important for the players to consider how the performance task is related to possible activities that can achieve the goal. For such mental activities, abduction and analogy play central roles in deepening the thinking that relates the problem with various activities which may not always be directly related to the problem domain. In Particular, analogical reasoning is quite useful to expose relationships which may not be directly related in the performance domain in question.

Knacks play crucial roles in acquiring artistic or sports skills. Generally knacks themselves are hard to understand. This is the reason why we call the secret as knack to perform difficult tasks. Abduction is a kind of synthetic reasoning used to construct explanatory hypotheses about knacks i.e. surprising observations. In this paper, we show how we have succeeded in applying abductive inference to provide explanation structure about how to perform difficult cello playing techniques, by exposing "hidden secrets" behind a given "knack" for achieving a difficult task.

Furthermore, we try to give proper explanation of a knack by employing analogical abduction. The role of abduction is to find explanation structure i.e. missing links in the explanation, whereas that of analogy gives understandable explanation to either the knack itself or the introduced links.

In realizing the analogical abduction engine, we integrate abduction and analogy on the basis of meta level expression of causality and analogy.

In Chapter 2, we discuss aspects of skill discovery in skill acquisition, focusing on two approaches; "meta cognitive verbalization" and "analogical abductive reasoning". In Chapter 3, we give formulation of skill acquisition by abduction. In Chapter 4, we augment abduction by analogy. In Chapter 5, we discuss other possibilities for explaining knacks. Lastly, in Chapter 6, we conclude our paper.

2. Aspects of Skill Discovery in Skill Acquisition

In acquiring any kinds of skill, an essential point is the mental activity of trying to discover a knack to perform a given difficult task. Knack discovery is essential in skill acquisition. Previously, we found the importance of closing one's right arm to increase sound volume in playing the cello as a case study [1, 2]. This is an example of a knack. Later, we discovered another knack to increase the sound by tilting the bow to touch to the string by the edge of the bow hair, which we call the "edge bowing method". These knacks provided significant improvement in achieving the given task.

The verbalization of a knack helps one to be more confident about acquired skills, both to deliver them to other people and to make them more objective. Among several approaches of skill verbalization, we especially notice two methods; "meta cognitive verbalization" [3, 4] and "analogical abductive reasoning" [5]. Meta cognitive verbalization tries to memorize one's physical status during performance in terms of notions which appeared in one's mind by self-reflection. By accumulating those memos for a long period of time, one can discover important facts within the change of vocabulary usage patterns, which reflects skill development.

On the other hand, analogical abductive reasoning tries to extract possible explanations how to perform given hard tasks by selecting adequate combinations of candidate hypotheses in a repertoire of body movement actions. For example, in our experimental study, we tried to find methods to perform "traverse between two strings repeatedly with bow direction change" and discovered a hypothesis "activate right forearm muscles strongly".

Skill acquisition has many issues to be addressed. Some are listed as follows;

i. finding a knack for skillful performance,
ii. finding missing links (secrets behind a knack) in skill explanation,
iii. identifying the role of a surprising fact (a knack) in skill discovery, and
iv. accommodating the new skill.

Interestingly, most of the issues listed above can be properly treated in the analogical abductive reasoning framework. In this paper, we focus on the skill of playing the cello. A player often exercises some basic methods at the first step of training. In some later steps, however, the player may face a passage which s/he cannot play by using only acquired methods. In such case, none of the acquired methods can be applied to the passage, so new methods are required. Typically, the passage in question contains compound tasks to be achieved simultaneously. In that case, simple adoption of component basic skills do not work properly; we need to invent a new skill to avoid potential inconsistency amongst the compound tasks: we call this process *skill abduction*. The new skill is called an abduced skill. The solution may be unexpected and hard to achieve. Our goal is to aid the player and/or the trainer to find a solution by analyzing the goal task, basic skills and relevant physical constraints.

3. Formulating Skill Acquisition by Abduction

3.1 Generating hypotheses by abductive reasoning

Although abductive reasoning does not necessarily derive the right answer, it produces plausible hypotheses to explain observation and therefore useful in hypotheses generation. The philosopher Pierce first introduced the notion of abduction. In Pierce [6] he identified three forms of reasoning.

Deduction, an analytic process based on the application of general rules to particular cases, with the inference of a result.

Induction, synthetic reasoning which infers the rule from the case and the result.

Abduction, another form of synthetic inference, but of the case from a rule and a result.

Peirce further characterized abduction as the "probational adoption of a hypothesis" as explanation for obsevations (results), according to known laws. "It is however a weak kind of inference, because we cannot say that we believe in the truth of the explanation, but only that it may be true" [6]. We omit formal definition of abductive inference to avoid complexity [7]. The essence of abductive inference is to augment missing facts or rules to derive the given surprising observation (the knack). Therefore an abductive inference engine is synonymous with a theorem prover augmented by a mechanism of finding missing links in deriving the given problem (a knack).

3.2 Logical explanation of a knack by abduction

Knacks are target-dependent and are expressed by such phrases as "if you want to achieve a target exercise *A*, you should do an action *B*." But it is typically difficult to explain why the action *B* works for achieving the exercise *A* because of either the existence of "hidden secrets" behind the knack or the lack of proper knowledge to understand the given knack. In this section we solve the former problem by applying abduction. The latter problem is solved in Chapter 4.

A knack is usually a surprising observation and therefore hypotheses generation by abduction can help in finding candidates for the "secret" prerequisite for achieving the given exercise. To elaborate, we try to abduce missing hypotheses to achieve (explain) the goal (exercise) *A* under the assertion of the fact (action) *B*. Since *B* appears at the leaf of the proof tree, the abduction procedure has to find hypotheses in between the goal *A* and the leaf *B*, identified as a (set of) rule(s). We refer to this abductive procedure as rule abduction. Note that rule abduction itself is realized in the framework of ATMS (Assumption based Truth Maintenance System) [8]. In this paper, we select logic programming approach because it is simpler and more expressive than ATMS. However, rule abduction cannot be achieved by standard Abductive Logic Programming (ALP) [7], because "abducibles" (predicates which are allowed to appear in the hypotheses to be generated) are limited only to "facts" in ALP. It means that generated hypotheses are simple (unknown) facts. A simple example of fact abduction is to explain the lack of a person's alibi by hypothesizing that he is a criminal. This limitation is due to the difficulty of handling rule abduction. To resolve this difficulty, we developed a rule abduction method using meta level abduction [2] where causality relations between predicates are expressed by a meta predicate "caused(X,Y)" which represents that the goal X is caused by an action Y. Note that we restrict the logical implication to causality. The detail of the meta level representation is described in the next section.

There may be a situation where a (set of) intermediate proposition(s) is necessary to fill a gap between the premise B of the knack and its goal A, in which case we need to invent a new node (predicate) between them. This ability is called as "predicate invention" in Inductive Logic Programming (ILP) community, which has been claimed to be very hard to realize. We found that SOLAR was equipped with this function naturally by virtue of the ability to produce hypotheses having variables with existing quantifier [2]. An example having his feature is shown later in subsection 4.3.2.

3.3 Meta level representation for rule abduction

A weakness of available abductive inference engines such as PrologICA [9] is that we can only abduce facts but not rules. As explained in the last section, we need rule abduction to explain why knacks work. Our approach to overcome this problem is to introduce meta level representation to express rules as atoms by introducing causality relations between predicates such as *caused*(*spiccato*, *bow_support_with_ringfinger*), which states that spiccato is caused by supporting the bow with the ring finger. This representation allows us to state a rule "spiccato is caused by supporting the bow with the ring finger" in terms of a meta level atom *caused*(*spiccato*, *bow_support_with_ringfinger*). Since we can abduce meta level atoms with a predicate *connected* (which represents a direct causality relation) by applying conventional abductive engines, we succeed in obtaining a rule "$spiccato \leftarrow bow\_support\_with\_ringfinger$." Formally, the predicate *caused* is defined recursively as follows:

$$caused(X,Y) \leftarrow connected(X,Y) \quad (1)$$
$$caused(X,Y) \leftarrow connected(X,Z), caused(Z,Y) \quad (2)$$

Here, the predicates *connected* and *caused* are both meta-predicates for object-level propositions X, Y and Z. From now on, we refer to this representation of causality relations as Meta Level (ML) representation of causality.

4. Augmenting Abduction by Analogy

4.1 Why analogical abduction?

Our rule abduction alone is insufficient to obtain meaningful missing prerequisites in the real application domain of skill acquisition. For example, consider this example of a knack: “you should bend the thumb joint to realize crossing strings quickly.” In this example, a possible missing rule is the knack itself; that is, “to achieve crossing strings quickly, bend the thumb joint” is a rule to be hypothesized by rule abduction. But it is easy to see that this rule is essentially useless because it does not explain why it works effectively. Here we introduce an analogical abduction system which makes it possible to give a suitable explanation to the proposed knack. To show the effectiveness of the knack, we need to identify a hidden reason. The hidden reason is typically provided by analogical reasoning which gives a possible explanation of the knack by means of an argument in an underlying analogical domain associated with the original vocabulary of the abducible rules.

Abductive reasoning generates possible hypotheses to prove a given knack to achieve a given difficult task. However it proposes only a possible proof (explanation) structure, i.e., the identification of missing links in the proof tree. It remains the user’s task to give an appropriate meaning to generated hypotheses. Analogical reasoning is a possible way to automatically identify potential meanings of generated hypotheses. For example, to give an explanation to the hypothesis “spiccato is directly caused by *bow_support_with_ringfinger*, we use an analogy to the dynamics of forced vibration which is known to be analogous to spiccato, that is, a fast jumping staccato. Furthermore we know that the forced vibration is directly caused by both supplying energy to the system with appropriate timing (just after the point of maximum amplitude) and absorbing shock at the point of energy supply. It is quite persuasive if we find a correspondence of *bow_support_with_ringfinger* to shock absorbing in forced vibration. We try to extract this correspondence automatically by incorporating analogical reasoning into an abduction engine SOLAR [10, 11].

4.2 Incorporating analogical reasoning to abduction

In this section, we incorporate analogical reasoning into our ML framework. We refer to the world under consideration as the target world and the corresponding analogical world as the base world. Analogical reasoning is achieved by introducing a base world similar to the target world, where we conduct inference [12]. Analogical reasoning can be formulated as logical inference with equality hypotheses [13]. We achieve analogical abduction by extending our ML based rule abduction framework.

We modify the causality relationship formula (1) and (2) to deal with causalities in the different worlds separately as follows:

$$
\begin{aligned}
&t\_caused(X,Y) \leftarrow t\_connected(X,Y)\\
&t\_caused(X,Y) \leftarrow t\_connected(X,Z),\ t\_caused(Z,Y)\\
&b\_caused(X,Y) \leftarrow b\_connected(X,Y)\\
&b\_caused(X,Y) \leftarrow b\_connected(X,Z), b\_caused(Z,Y)
\end{aligned} \tag{3}
$$

where the prefix "*t"* represents a predicate in the target world and "*b"* in the base world. Although the predicate "*b_caused*" does not appear in following examples, we define it because of the symmetry with "*t_caused*" for possible future use. We also introduce a predicate "*similar*(*X, Y*)" to represent similarity relations between an atom *X* in the target world and a corresponding atom *Y* in the base world.

Now we have to define the predicate "*t_connected*," for which we have to consider three cases to show the connectedness in the target world as follows:

$$t\_connected(X,Y) \leftarrow connected\_originally(X,Y) \tag{4}$$

$$t\_connected(X,Y) \leftarrow connected\_by\_abduction(X,Y) \tag{5}$$

$$t\_connected(X,Y) \leftarrow connected\_by\_analogy(X,Y) \wedge print\_connected\_by\_analogy(X,Y) \tag{6}$$

The first case is that the connectedness holds from the beginning, (4); the second case is that it holds by abduction as a solution of abductive inference, (5); and the third case is that it is derived by analogy, (6). Definition (6) contains an auxiliary predicate "*print connected by analogy*(*X*, *Y*)" which indicates that it is to be "*printed*" as a part of an abduced hypothesis to provide evidence that the analogical connection is actually used to show the "*t_connected*"ness. Since analogical reasoning can be achieved without any defects in the inference path, we need to prepare an artificial defect atom "*print_connected_by_analogy*(*X*,*Y*)" on the reasoning path. This printing in turn is defined by specifying the predicate "*print_connected_by_analogy*" as an abducible predicate.

We have to further define three predicates; "*connected_originally*", "*connected_by_abduction*" and "*connected_by_analogy*". The predicate "*connected_originally*" is used in the assertion of facts representing the original connection; "*connected_by_abduction*" is introduced as an abducible predicate. Finally, the definition of "*connected_by_analogy*" is given by the following analogy axiom which plays a central role in analogical abduction.

Analogy Axiom

$$connected\_by\_analogy(X,Y) \leftarrow b\_connected(XX, YY),\ similar(X,XX), similar(Y,\ YY) \tag{7}$$

This axiom states that the nodes *X* and *Y* in the target world can be linked by the predicate "*connected_by_analogy*(*X*, *Y*)" because of the base relationship "*b_connected*(*XX, YY*)" between *XX* and *YY* which are similar to *X* and *Y*, respectively, as shown in Figure 1. Note that there may be more than one similarity candidates. In this paper, we assume that the user provides some of the initial similarities, and that the abductive inference engine will compute any remaining possible similarity hypotheses to explain an observation.

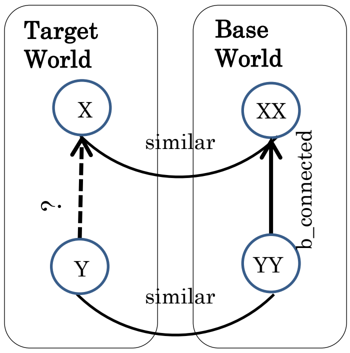

Figure 1 A schema representing the Analogy Axiom.

4.3 Giving analogical explanation to generated hypotheses

4.3.1 Interpreting a causal link by analogy

We first start with an example of a simple analogical abduction. The problem is ho to explain the effectiveness of holding the bow by the ring finger.

```
% Observation (G) :
t caused(spiccato, support_bow_with_ringfinger).                         (8)
% Abducible predicates( Γ ) :
abducibles([connected_by_abduction/2, similar/2,
print_connected_by_analogy/2]).
% Background Knowledge(B) :
%%% Base world:
b_connected(forced_vibration, shock_absorber).                           (9)
%%% Target world:
:-connected_by_abduction(spiccato, support_bow_with_ringfinger).        (10)
% Similarity:
similar(spiccato, forced_vibration).                                    (11)
%Axioms:
b_caused(X; Y):-b_connected(X, Y).
b_caused(X, Y):-b_connected(X, Z), b_caused(Z, Y).
t_caused(X, Y):-t_connected(X, Y).
t_caused(X, Y):-t_connected(X, Z), t_caused(Z, Y).
t_connected(X, Y):-originally_connected(X, Y).
t_connected(X, Y):-connected_by_abduction(X, Y).
t_connected(X, Y):-connected_by_analogy(X, Y),
                    print_ connected_by_analogy(X, Y).
```

connected_by_analogy(X, Y):-b_ connected(XX, YY), similar(X, XX),
similar(Y, YY). (12)

In this program, the goal (observation) to be satisfied is "t_caused(spiccato, support_bow_with_ringfinger)" (Clause 8). We provide the following two facts: 1) "shock_absorber" is one of the possible causes to achieve the forced_vibration (Clause 9), and 2) spiccato is analogous to the forced_vibration (Clause 11). In addition, we provide a negative clause asserting that the direct connection from "support_bow_with ringfinger" to "spiccato" cannot be hypothesized (Clause 10). In one of our SOLAR experiments, the number of obtained hypotheses is 7 when the maximum search depth is set to 10 and the maximum length of produced clauses is 4. One plausible hypothesis is:

print_connected_by_analogy(spiccato, support_bow_with_ringfinger) ∧
similar(support_bow_with_ringfinger, shock_absorber)

which indicates that the support of the bow with the ring finger in spiccato is analogous to the shock absorber in the forced vibration as shown in Figure 2.

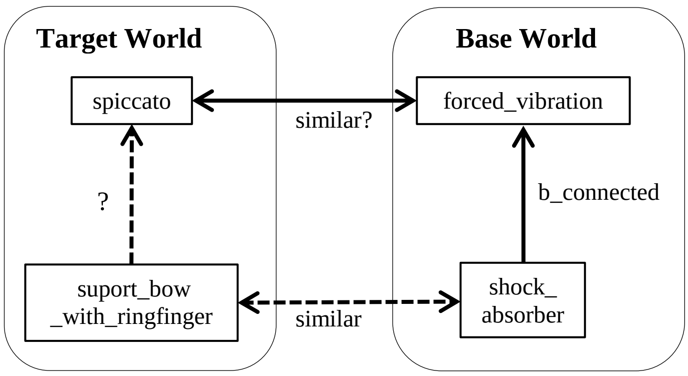

Figure 2. Analogical abduction for achieving spiccato playing. The dotted lines are to be computed as a hypothesis.

4.3.2 Interpreting a newly invented predicate by analogy

In this subsection, we consider the problem of showing the effectiveness of bending the thumb to achieve the quick crossing of strings (cross strings quick). We use the skeletal structural linkage of the knuckle (of the first four fingers) and the thumb (b_ connected(knuckle, thumb)) as a counterpart of a functional linkage of bending the knuckle and bending the thumb (t connected(knuckle bend, thumb bend)) in the analogy setting. Note that we define the similarity only between "bending thumb" and "thumb" without providing the predicate "bend knuckle", which is to be invented by abductive reasoning. In this example, we discover missing similarities and invent a predicate at the same time. The problem structure is shown in Figure 3.

The abduction program for this problem is shown as follows (axiom clauses are omitted here):

```
% Observation(G) :
t_caused(cross_strings_quick, bend_thumb).
% Abducible predicates( Γ ) :
abducibles([connected_by_abduction/2, similar/2,print_connected_by_analogy/2]).
% Background Knowledge(B) :
%%% Base world:
b_connected(knuckle, thumb),
%%% Target world:
:-connected_by_abduction(cross_strings_quick, bend thumb).
% Similarity:
similar(bend_thumb, thumb).
```

Under the same condition as before, we obtained 7 hypotheses, one of which is the following:

connected_by_abduction(cross strings quick, X) ∧
similar(X, knuckle) ∧
print_connected_by_analogy(X, bend thumb)

This hypothesis accurately represents the structure shown in Figure 3. We further conducted our experimental study by deleting the similarity relation "similar(bend_thumb, thumb)" from the above program and then succeeded in recovering this link as well.

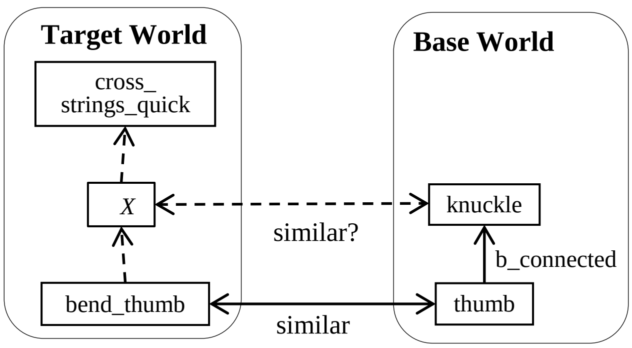

Figure 3. Analogical abduction with predicate invention. A predicate *X* is introduced by abduction in Target World. An analogical reasoning is conducted to give an interpretation of *X* as similar to "knuckle" in the Base World.

4.4 Explaining the Effectiveness of Metaphorical Expression

To show the applicability of our approach to different kinds of problems other than mechanical models, we apply our analogical abduction to explain the effectiveness of a metaphorical expression. An example of metaphorical expression, issued by a trainer to achieve forte-piano dynamics in orchestra rehearsal, is "eating pancake on the sly," which means that one takes a big mouthful of pancake first, and then he/she tries to make it secret by a motion of imperceptible action of chewing. The difficulty of achieving such dynamics arises because we cannot control our muscle strength accurately because of an inability to precisely estimate force. In addition, it is quite difficult to attain consensus amongst players about the shape of the dynamics envelope. But a metaphorical expression can sometimes help achieve a consensus. This phenomenon is formalized in terms of our analogical abduction framework. Our goal is to prove "t_caused(forte_piano, eat_pancake_on _the_sly)". We assume that the expression "eating pancake on the sly" induces a sequence of motor control commands indicating a big action followed by an imperceptible action in the brain, which arises within the metaphorical base world (see Figure 4). The analogical abductive reasoning is shown as follows:

```
% Observation(G) :
t_caused(forte piano; eat pancake on the sly).
% Abducible predicates(Γ) :
abducibles([connected by abduction/2, similar/2, print_connected_by_analogy/2]).
% Background Knowledge(B) :
%%% Base world:
b_connected(big_then_impercep_action,  eat pancake on the sly).
%%% Target world:
:-connected_by_abduction(forte_piano, eat_pancake_on_the_sly).
```

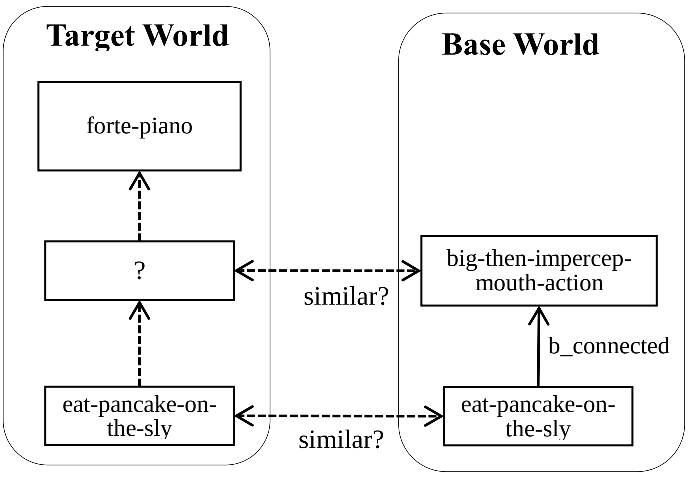

Figure 4. Mataphorical expression of "eating pancake on the sly" to achieve forte-piano.

Under the same condition as before, we obtained 6 hypotheses, one of which is the following:

connected_by_abduction(forte_piano, X) ∧
similar(X, big_then_impercep_action) ∧
similar(eat_pancake_on_the_sly, eat_pancake_on_the_sly) ∧
print connected by analogy(X, eat_pancake_on_the_sly)

Note that the third atom has the form "similar(X,X)". Namely we regard the same thing as similar.

The entire problem structure of this analogical abduction is almost the same as our previous predicate invention example shown in Figure 3 except for the treatment of the similarity relation at the bottom; it is abduced in the metaphorical analogy case whereas it is given from the beginning in Figure 3. The key characteristics of the metaphorical analogy is that the same analogical expression appears in both the base and the target worlds. Since a metaphorical expression directly induces an emotional feeling to encourage the production of adequate motor control commands for achieving the given goal, it should be included in the target world. Alternatively, the same metaphorical expression triggers a similar motion in the eating action which means that it should be in the base world. Another remark is that the metaphorical expression of "eating pancake on the sly" plays the role of converting a quantitative direction of the sound volume adjustment into a qualitative one, which is much more intuitive and understandable.

5. Other possibilities for Explaining Knack

In the last section, we showed the usefulness of analogical abduction as a promising way to produce persuasive explanative arguments for understanding the reason why the given knacks work well in performing difficult tasks. Abduction finds the location of missing links in the proof tree and analogy gives interpretation of the found links including both a causal link and a newly introduced predicate.

This chapter discusses other possibilities for explaining the idea of a knack. For example, while studying the one-bow staccato technique, we found the importance of holding the bow while stretching the thumb contrary to ordinal bow-holding. In fact, this knack is very useful in increasing the bow stability during the one-bow staccato performance. However, this consequence was not understood easily by the learners before observing a performance video showing virtuoso technique of the one-bow staccato. By looking the video, most of the learners suddenly understood the role of the new bow-holding way which can be expressed as pinching by the thumb and other fingers. This experience supports the usefulness of observing skillful videos to understand the key points of the knack.

Another experience supports the importance of metaphorical expression for delivering a sense of musicality in ensemble performance. We introduced the example metaphorical expression "eating pancake on the sly," where we claimed that such an expression sometimes helps achieve a consensus among players. Precisely speaking, this situation is not a knack explaining problem. However it provides all the players a common musical feature how to play the given note having the "forte-piano" sign. Therefore it is a musicality explaining problem which is closely related to knack explaining. Furthermore, we succeeded in formulating this "forte-piano" expression problem in terms of our analogical abduction framework.

6. Discussion and Future work

We have discussed the feasibility of our analogical abduction in skill acquisition. In acquiring skills, we need to understand adequate knacks to achieve given difficult performance tasks like spiccato or rapid cross strings of bow movement in cello playing. There are two kinds of activities required to obtain such knacks: to encounter such knacks and to assimilate and/or accommodate them to their own knowledge. The problem of encountering knacks is achieved in various ways: being taught by teachers, by watching good performance, by trial and error by themselves and so on. A possible scientific support for this encountering is physical meta cognition [3,4]. In this paper, we focused on the accommodation aspect in knack acquisition. We discussed the importance of knack explanation to achieve the accommodation problem. Analogical abduction plays an essential role in this mental processes, since we need a precise explanation why a given knack is useful in achieving the given performance task. Analogical abduction gives an explanatory argument to achieve a task by showing the validity of the knack as a proof in causality links and analogical arguments.

There is another fundamental issue to be addressed to achieve more realistic analogical abduction. In this paper, we explicitly provide a base world analogous to the target world. In real problems for discovering or explaining skills, we may need to find an appropriate base world itself, before being able to conduct analogical reasoning, or to find and extract similar sub-worlds adequate for analogical abduction from the given target and base worlds. To deal with these problems, we have to provide detailed attributes to the components of each world and compute the degree of similarity for each pair of subset to find analogous pairs [14].

In our approach, we put an abduction engine in the center and tried to add analogical reasoning on top. However, there are other possibilities to generalize our approach further to find better integration of abduction and analogy, including metaphor. One viewpoint is to make analogical reasoning propose adequate abducibles for abduction. This should by realized by strengthening abductive reasoning engine by adding the feature of automatic preparation of abducibles supported by analogical reasoning. Another viewpoint is to use abduction to propose appropriate similarity relations to establish analogical reasoning, which has been reported here. In other words, abduction and analogy are supporting each other. An ideal implementation of a complementary abduction-analogy system is future research work.

Finally, we notice the importance of ML representation of causality and analogical reasoning. At first, we introduced the ML representation to realize rule abduction. Later we succeeded in realizing analogical reasoning by adding an analogy axiom with the predicate "*connected_by_analogy*(*X, Y*)" as well as the similarity predicate "similar(*X, Y*)". Note that both predicates are meta predicates both of whose arguments are propositions. In a sense, the ML representation made it possible to concisely augment the functionality of analogical reasoning to our rule abduction system. It is interesting to note that rule abduction and analogical reasoning are important aspects of human cognitive functions. This leads an important suggestion that ML representation may work as a key role in human thinking. The handling of metaphor is another evidence of this conjecture. There are remaining researches to promote this idea further.

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