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A Rule-Based Implementation of ACT-R Using Constraint Handling Rules

Masterarbeit an der Universität Ulm

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Abstract

This is the abstract of my master thesis.

Contents

1	Introduction	1
2	Description of ACT-R	3
2.1	Procedural and Declarative Knowledge	4
2.1.1	Modular organization	4
2.1.2	Declarative Knowledge	5
	Buffers	5
2.1.3	Procedural Knowledge	6
	Description of Procedural Actions	7
	Chunks as Central Data Structure	7
	Process of Rule Selection and Execution	8
2.1.4	Goal Module	8
	Working memory	8
2.1.5	Other Modules	9
	The Outside World	9
	The Imaginal Module	10
2.1.6	Example	11
2.2	Serial and Parallel Aspects of ACT-R	12
2.3	Subsymbolic layer	13
2.3.1	Activation of Chunks	13
	Base-Level Activation	14
	Activation Spreading	15
	Latency of Retrieval	17
2.3.2	Production Utility	17
2.4	Learning	18
3	Constraint Handling Rules	19
4	Transformation of ACT-R to CHR	21
4.1	Chunk Stores	21
4.1.1	Formal Representation of Chunks	21
4.1.2	Representation of Chunks in CHR	23
	Simple Implementation of the Default Methods	24

Contents

Checking Type-Consistency	25
4.2 Procedural Module	25
4.2.1 Buffer System	25
Destructive Assignment and Consistency	26
Buffer States	26
4.2.2 Production Rules	26
4.3 Modular Organization	27
4.4 Declarative Module	28
4.4.1 Retrieval Requests	28
4.5 Timing in ACT-R	28
4.5.1 Priority Queue	28
4.6 Subsymbolic Layer	28
4.6.1 Activation of Chunks	28
4.6.2 Production Utility	28
5 Compiler	29
6 Example Models	31
6.1 The Counting Model	31
6.2 The Addition Model	31
6.3 The Semantic Model	31
6.4 The Fan Model	31
7 Conclusion	33
7.1 Inventory: What does already work?	33
7.2 Future Work	33
A Source Codes	35
Bibliography	37

1 Introduction

2 Description of ACT-R

In computational psychology, the approach to explore human cognition is to implement detailed computational models that enable computers to execute them and simulate human behaviour [Sun08]. By conducting the same experiments with humans and with simulations of the suggested underlying cognitive models, the plausibility of models can be checked and models can be improved gradually.

On the other hand, psychology is experiencing a movement towards specialization [ABB⁺04], ie. there are a lot of independent, highly specialized fields that lack a more global view.

To implement consistent models of cognition, it is necessary to develop a theory that tries to put all those highly specialized components together and allows modelers to build their models on the basis of this theory. Cognitive architectures try to explain

FIXME: definition cognitive architecture from book **FIXME: move to introduction and motivation**

Adaptive Control of Thought-Rational (ACT-R) is a cognitive architecture, that “is capable of interacting with the outside world, has been mapped onto brain structures, and is able to learn to interact with complex dynamic tasks.” [TLA06, p. 29]

On top of the provided cognitive architecture, one can specify models for specific tasks. The cognitive architecture constrains the modeling to facilitate the modeling process. Thereby it ensures cognitive plausibility to some degree, since models are built upon a highly verified theory [TLA06, p. 29].

When talking about ACT-R, one can refer to the theory or the implementation. The theory gives a view which abstracts from implementational details that may be concerned when talking about implementation **FIXME: source**. In this work, implementation always refers to the vanilla Lisp implementation that can be downloaded from [act].

In this chapter, a short overview over the theory of ACT-R is given. First, the description is informal to provide a general image of how ACT-R works. Then, some important parts of the system are defined more formally in chapter ??, as soon as it is needed in the implementation. All of the information in this chapter refers to the theory. Implementation is discussed in chapter ??.

2.1 Procedural and Declarative Knowledge

A central idea of ACT-R is the distinction between *declarative* and *procedural knowledge*. The declarative knowledge consists of simple facts, whereas the procedural knowledge contains information on what to do with those facts.

2.1.1 Modular organization

This approach leads to a modular organization of ACT-R with modules for each purpose needed to simulate human cognition. Figure ?? provides an overview of some of the default modules of ACT-R. For example, the declarative module stores the factual information (the declarative knowledge), the visual module perceives and processes the visual field, the procedural module holds the procedural information and controls the computational process.

Each module is independent from the other modules and computations in the modules can be performed parallel to other modules, for instance: The declarative module can search a specific fact while the visual module processes the visual field.. Additionally, within one module computations are executed massively parallel, eg. the visual module can process the entire visual field at once to determine the location of a certain object, which implies the processing of a huge amount of data at a time.

However, each module can perform its computation only locally and has no access to computations of other modules. To communicate, modules have associated *buffers*, where they can put a limited amount of information – one primitive knowledge element – and the procedural module can access each of these buffers. The information in a buffer could be one single fact retrieved from declarative memory or one visual object from the visual field perceived by the visual module. Information between modules is exchanged by the procedural module taking information from one buffer and putting it into another (with an optional computation on the way). This leads to a serial bottleneck in the computation, since every communication between modules has to go its way through the procedural module.

In figure ?? the general computational process is illustrated by showing the *recognize-act-cycle*: The procedural information is stored as rules that have a *condition* and an *action*. The condition refers to the so-called *working memory*, which basically is the content of all the buffers. In the recognize-phase of the cycle, a suitable rule that matches the current state of the working memory is searched. If the condition of a rule holds, it *fires* and performs its actions – this is the act-phase of the cycle. Those actions can cause changes on the buffers

that may lead to the next rule matching the current state in the next recognize-part of the cycle.

In the following sections, some of the modules and their precise interaction will be described in more detail.

2.1.2 Declarative Knowledge

The declarative module organizes the factual knowledge as an associative memory. I.e., it consists of a set of concepts that are connected to each other in a certain way.

Such elementary concepts are represented in form of chunks that can be seen as basic knowledge elements. They can have names, but they are not critical for the description of the facts and just for readability in the theory. The real description of a concept comes from its connections.

Chunks can have slots that are connected to other chunks or elements. Such an element can be regarded as a chunk without any slots. For instance, the fact that five plus two equals seven can be modeled as a chunk that is connected to the numbers 5, 2 and 7 (see ??). Notice that in the figure each slot has a individual name. This is necessary to distinguish the connections of the chunks, otherwise the summands were indistinguishable from the sum in the example.

Each chunk is associated with a chunk-type that determines which slots a chunk can have. For example, the fact in figure ?? has the type `addition-fact`. All chunks of this type must provide the slots `arg1`, `arg2` and `sum`.

For the chunk types there is no upper limit of slots they can define. However, Anderson et al. suggested to limit the number of slots to Miller's Number of 7 ± 2 , for the reason of plausibility [?]. **FIXME: Find cite**

Buffers

As mentioned before, modules communicate through buffers by putting a limited amount of information into their associated buffers. More precisely, each buffer can hold only *one chunk at a time*.

2 Description of ACT-R

For example, the declarative module has the retrieval buffer associated with it, which can hold one specific declarative chunk. The declarative module can put chunks in the buffer that can be processed by the procedural module, which is described in the next section.

2.1.3 Procedural Knowledge

Procedural Knowledge in ACT-R is formulated as a set of condition-action rules. Each rule defines in its condition-part the circumstances under which it can be applied. Those conditions refer to the current chunks in the buffer. In the condition-part of a rule it is defined which kind of chunk with certain slot values must be present in which buffer for the rule to fire. For example, one rule in the process of adding the numbers 5 and 2 could have the conditions that there is a chunk of type `addition-fact` in the retrieval buffer with 5 and 7 in its argument-slots and specify certain actions if this is the case.

If the chunks in the buffers match all the conditions stated in a rule, it can be applied (“fired”), which leads its action-part to be performed. Actions can be changes of values in the chunks of a buffer, the clearing of a buffer or a buffer request, which leads the corresponding module to put a certain chunk into the requested buffer. Buffer requests are also stated in form of a (partial) chunk description¹ where chunk-type and slots can have a special meaning. The actual semantics of a request is dependent on the module. For example, the declarative module will search a chunk that matches the chunk in the description of the request. One production rule, for instance, in the process of adding the numbers 5 and 2 could be, if the wrong `addition-fact` chunk is stored in the retrieval buffer, a retrieval request will be performed, which states that the declarative module should put a chunk into the retrieval buffer, that has 5 and 2 in its argument slots and is of type `addition-fact`. After the successful performance of the request, a chunk with 5 and 2 as its argument will be stored in the retrieval buffer, that also has a value for the sum. The actions are described in more detail in the following section.

Although the term *module* is used for the procedural system, it differs a lot from the other modules: In contrast to other modules, the procedural module has no own buffers, but can access the buffers of all the other modules. “It really is just a system of mapping cortical buffers to other cortical buffers” [And07, p. 54].

The procedural system can only fire one rule at once and it takes 50 ms for a rule to fire [And07, p. 54]. After firing the selected rule, the next recognize cycle starts and a suitable rule will be detected and caused to fire. While that time, other modules may perform requests

¹A partial chunk description is just a chunk description that does not specify all slots that are available as defined in the chunk-type.

triggered in the action of the first rule. Sometimes, rules have to wait for results of certain modules and they cannot fire before those results are available. Those two facts illustrate how the procedural module can become a serial bottleneck in the computation process.

Description of Procedural Actions

In this section, the actions that can be performed by a production rule are described in more detail than before.

Buffer Modification: An in-place operation, that overwrites the slot values of a chunk in a buffer with the specified values in the action of the rule.

Buffer Request: A buffer request will cause the corresponding module to calculate some kind of result that will be placed into the requested buffer. The input values of this computation are given as chunks with a type and slot-value pairs specified in the request. For instance, the declarative module could search for a chunk that has the specified values in its slots.

The request is independent of the execution of the production rule and after the request has been stated by the procedural module, it can begin with the next recognize-cycle.

Before the request is performed, the corresponding buffer will be cleared.

Buffer Clearing: If a buffer is cleared, its containing chunk will be placed into the declarative memory from where it can be retrieved later on.

Chunks as Central Data Structure

As may have become clear in the previous sections, chunks are the central data structures in ACT-R. They are used to model factual knowledge in the declarative memory, but are also used for communication: Requests are stated as chunks that encode the input of the request, for instance a chunk pattern for a result chunk the declarative memory should retrieve.

The results of a request is a chunk placed into a buffer and even the procedural system tries to match the chunks in the buffers in the condition part and the action of a rule is specified by slot-value pairs that are basically just partial chunk descriptions.

Process of Rule Selection and Execution

As stated above, the procedural module can execute only one rule at a time. If no rule has been selected to fire and is in progress, the procedural module is *free* and therefore can select a matching rule according to the recognize-act-cycle. If the rule has been selected, the module is *busy* and cannot choose another rule to fire. Between selection and firing of a rule the module has to wait 50 ms. Then all in-place actions of the rule like modifying or clearing a buffer are performed. Afterwards, the requests are stated and the module is free. However, the requested modules most likely will take a certain time to perform the request. During this time the procedural module can select and fire the next matching rule nevertheless.

If at a certain time the procedural module is free, but there are no matching rules, the module waits, until the system reaches a state, where a rule matches. This is possible, since requests can take a certain time, where the procedural module is free and cannot find a matching rule. If the request has been performed, it usually has a change of buffers as an effect. At this point of time, when the content of a buffer has changed, this could cause the next rule to match and fire.

2.1.4 Goal Module

An essential part of human cognition is the ability to keep track of the current goal to achieve and to subordinate all actions to the goal [ABB⁺04, p. 1041]. For complex cognitive tasks, several rules have to be applied in series and intermediate results must be stored (without changing of the environment). Another important aspect is, that complex tasks can have different subgoals that have to be achieved to achieve the main goal. For instance, if one wants to add two multi-digit numbers, he would add the columns and remember the results as intermediate results.

In ACT-R, the goal module with the goal buffer is used for this purpose.

Working memory

The goal module and buffer are often referred to as *working memory* [ABB⁺04, p. 1041], but actually it can have another meaning as stated in [ARL96]: As usual in production systems, everything that is present to the production system and can match against the production

rules is part of the working memory. With this definition, all chunks in the buffers form the working memory.

In this work, the term working memory will be used in this second meaning, since it discusses the topic from a computer science view and the second definition is related to production rule systems. When talking about the content of the goal buffer, this will be remarked explicitly.

2.1.5 Other Modules

In figure ?? some more modules are shown. In the following, a short description of some of those modules is given.

The Outside World

Since human cognition is embodied, there must be a way to interact with the outside world to simulate human cognition in realistic experiments. Therefore, ACT-R offers *perceptual/motor modules* like the manual module for control of the hands, the visual module for perceiving and processing the visual field or the aural module perceiving sounds in the environment.

Like with every other module, communication is achieved through the buffers of those modules.

The Visual Module The visual system of ACT-R separates vision into two parts: visual location and visual objects [ABB⁺04, p. 1039]. There are two buffers for those purposes: the *visual-location* buffer and the *visual* buffer, which represents the visual objects [act12, unit 2].

In the visual module it is not encoded how the light falls on the retina, but a more attentional approach has been chosen [ABB⁺04, p. 1039].

Requests to the visual-location buffer specify a series of constraints in form of slot-value pairs and the visual module puts a chunk representing the location of an object meeting those constraints into the visual-location buffer. Possible constraints are properties of objects like the color or the spatial location. The visual system can process such requests in parallel, ie. that the whole visual field is processed massively parallel and the time of finding one green object surrounded by blue objects is constant, regardless of the number of blue objects, for

2 Description of ACT-R

example. If there are more than one object meeting the constraints, then one will be chosen at random [ABB⁺04, p. 1039], [And07, p. 68].

Requests to the visual-object system specify a visual location and the visual module will move its attention to that location, create a new chunk representing the object at that location and put that chunk into the visual buffer [act12, unit 2, chapter 2.5.3].

The visual system and its capabilities are described in detail in [act12, unit 2] and also regards the implementational details of the system.

The Imaginal Module

The imaginal module is capable of creating new chunks. This is useful, if for instance the visual module produces a lot of new information in sequence (like reading a sequence of letters). The visual-object buffer can hold only one chunk at once. A solution could be, to save all the information in slots of the goal chunk. However, since a goal chunk with a large amount of slots seems to be unfeasible² and the number of read instances would have to be known in advance due to the static chunk-type definition, the best way would be to create new knowledge elements.

This task can be achieved by using the imaginal module: On a request, it creates a new chunk of the type and with the slots stated in the request and puts it into its *imaginal buffer*. Since with every clearing of a buffer the chunk in that buffer is stored in declarative memory³, a unlimited amount of data can be produced and remembered by stating retrieval requests later on.

It is important to mention, that it takes the imaginal module .2 ms to create a chunk. This amount of time is constant, but can be set by the modeler. Additionally, the imaginal module can only produce one chunk at a time⁴.

The imaginal module is described in [act12, unit 2].

²As described in section 2.1.2, one should stick to 7 ± 2 slots for each chunk.

³see section 2.1.3

⁴like every module can only handle one request at a time

2.1.6 Example

The first ACT-R example model deals with the process of counting. This model relies on count facts a person has learned, eg. "the number after 2 is 3". To model this in ACT-R, a chunk-type for those facts has to be defined: A chunk of type *count-fact* has the slots *first* and *second*. The chunks in figure ?? of this type *count-fact* model the facts that 3 is the successor of 2 and 4 is the successor of 3.

The next step is to define the goal chunk stored in the goal buffer. In this chunk it somehow has to be encoded, that the current goal is to count. This can be modeled in ACT-R by the chunk-type. To track the current number in the counting process, the goal chunk could have a slot, that always holds the current number that has been counted to. This leads to a goal chunk as illustrated in figure ??, where the current number is 2. In this example we assume that the model starts with this goal chunk in the goal buffer and the first count fact has been retrieved:

goal buffer: goal-chunk of type count
current-number 2

retrieval buffer: b of type count-fact
first 2
second 3

Now the rules to implement counting can be defined as:

count-rule If the goal is to count and the current number is n and the retrieval buffer holds a chunk of type *count-fact* with the *first* value n and the *second* value m , then set the current number in the goal to m and send a retrieval request for a chunk that has m in its *first* slot.

The rule matches the initial state: In the goal there is a chunk of type *count*, that indicates that the goal is to count, the current number n is 2. In the retrieval buffer, there is a *count-fact* with the *first* number $n = 2$ and the *second* number $m = 3$.

After applying this rule, the current number will be 3 and the next fact in the retrieval buffer will be a *count-fact* with the *first* value 3 and a value in the *second* slot, which will be the next number in the counting process. This illustrates the function of module requests: The request states a (potentially partial) chunk definition and the corresponding module puts the result of the request in a fully defined chunk into its buffer. For the declarative module, the request specifies the chunk-type and some slot values which describe the chunk that the module should be looking for. The result is a fully described chunk of that type with values for all slots, that describe an actual chunk from the declarative memory.

2 Description of ACT-R

The count-rule will be applicable as long as there are *count-facts* in the declarative memory. Figure ?? illustrates the counting process.

In this example, the rules have been defined in a very informal way. In the following chapters that deal with implementation, a formalization of such rules will be discussed, that defines clearly, what kinds of rules are allowed and introduces a formalism to describe such rules uniquely and less verbosely. The following chapters will refer to this example and refine it gradually.

The example also uses the concept of *variables*, which will be introduced more formally in chapter ??, when talking about implementation. Variables allow rule conditions to act like patterns that can match various system states instead of defining a rule for each state, since computation is the same regardless of the actual values in the buffers.

FIXME: figures

2.2 Serial and Parallel Aspects of ACT-R

In the previous sections there were some remarks on the serial and parallel aspects of ACT-R. According to [And07, p. 68], four types of parallelism and seriality can be distinguished:

Within-Module Parallelism: As mentioned above, one module is able to explore a big amount of data in parallel. For example, the visual module can inspect the whole visual field or the declarative module performs a massively parallel search over all chunks.

Within-Module Seriality: Since modules have to communicate, they have a limited amount of buffers and each of those buffers can only hold one chunk. For example, the visual module only can concentrate on one single visual object at one visual location, the declarative module only can have one single concept present, the production system can fire only one rule at a time, . . .

Between-Module Parallelism: Modules are independent of each other and their computations can be performed in parallel.

Between-Module Serialism: However, if it comes to communication, everything must be exchanged via the procedural module that has access to all the buffers. Sometimes, the production system has to wait for a module to finish, since the next computation relies on this information. So, modules may have to wait for another module to finish

its computation before they can start with theirs triggered by a production rule that states a request to those modules.

The procedural module is the central serial bottleneck in the system, since the whole communication between modules is going through the production system and the whole computation process is controlled there. The fact that only one rule can fire at a time leads to a serial overall computation. Another serial aspect is that some computations need to wait for the results of a module request. If no other rule matches in the time while the request is performed, the whole system has to wait for this calculation to finish. After the request, the module puts the result in its buffer and the rule needing the result of the computation can fire and computation is continued.

2.3 Subsymbolic layer

The previously discussed aspects of the ACT-R theory are part of the so-called symbolic layer. This layer only describes discrete knowledge structures without dealing with more complex questions like:

- How long does it take to retrieve a certain chunk?
- Forgetting of chunks
- If more than one rule matches, which one will be taken?

Therefore, ACT-R provides a subsymbolic layer that introduces “neural-like activation processes that determine the availability of [...] symbolic structures” [AS00].

2.3.1 Activation of Chunks

The activation A_i of a chunk i is a numerical value that determines if and how fast a chunk can be retrieved by the declarative module. Suppose there are two chunks that encode addition facts for the same two arguments (let them be 5 and 2), but with different sums (6 and 7), for example. This could be the case, if a child learned the wrong fact, for example. When stating a module request for an addition fact that encodes the sum of 5 and 2, somehow one of the two chunks has to be chosen by a certain method, since they are both matching the request. This is determined by the activation of the chunks: The chunk with the higher activation will be chosen.

2 Description of ACT-R

Additionally, a very low chunk activation can prevent a chunk of being retrieved: If the activation A_i is less than a certain *threshold* τ , then the chunk i cannot be found.

At last, activation determines also how fast a chunk is being retrieved: The higher the activation, the shorter the retrieval time.

Base-Level Activation

The activation A_i of a chunk i is defined as:

$$A_i = B_i + \Gamma \quad (2.1)$$

where B_i is the *base-level activation* of the chunk i . Γ is a context component that will be described later on. Equation (2.1) is a simplified variant of the *Activation Equation*.

The base-level activation is a value associated with each chunk and depends on how often a chunk has been practiced and when the last retrieval of the chunk has been performed. Hence, B_i of chunk i is defined as:

$$B_i = \ln \left(\sum_{j=1}^n t_j^{-d} \right) \quad (2.2)$$

where t_j is the time since the j th practice, n the number of overall practices of the chunk and d is the decay rate that describes how fast the base-level activation decreases if a chunk has not been practiced (how fast a chunk will be forgotten). Usually, d is set to 0.5 [ABB⁺04, p. 1042]. Equation (2.2) is called *Base-Level Learning Equation*, as it defines the adaptive learning process of the base-level value.

This equation is the result of a rational analysis by Anderson and Schooler. It reflects the log odds that a chunk will reappear depending on when it has appeared in the past [TLA06, p. 33]. This analysis led to the *power law of practice* [ABB⁺04, p. 1042]. In [AS00, pp. 8–11] equation (2.2) is motivated in more detail by describing the power law of learning/practice, the power law of forgetting and the multiplicative effect of practice and retention with some data. Shortly, it states, that if a particular fact is practiced, there is a improvement of performance which corresponds to a power law. At the same time, performance degrades with time

corresponding to a power law. Additionally, they state that if a fact has been practiced a lot, it will not be forgotten for a longer time.

Activation Spreading

In ACT-R, the basic idea of activation is, that it consists of two parts: The base-level component described above, and a context component. Every chunk that is in the current context has a certain amount of activation that can spread over the declarative memory and enhance activation of other chunks that are somehow connected to those chunks in the context. The activation equation (2.1) is extended as follows:

$$A_i = B_i + \sum_{j \in C} W_j S_{ji} \quad (2.3)$$

where W_j the *attentional weighting* of chunk j , S_{ji} the *associative strength* from chunk j to chunk i and C is the *current context*, usually defined as the set of all chunks that are in a buffer [ABB⁺04, p. 1042], [TLA06, p. 33], [act12, unit 5]. Figure ?? illustrates the addition-fact $5 + 2 = 7$ with the corresponding quantities introduced in the last equation.

The values for W_j reflect how many sources of activation are in the current context. A source of activation is a chunk in the goal buffer or in all buffers⁵, depending on the version of the ACT-R theory [ABB⁺04, p. 1042], [TLA06, p. 33], [act12, unit 5, p. 1]. To limit the total amount of source of activation, W_j is set to $\frac{1}{n}$, where n is the number of sources of activation. With this equation, the total amount of activation that can spread over declarative memory is limited, since the more chunks are in the current context, the less important becomes a particular connection between a chunk from the context with a chunk from declarative memory.

Strength of Association and Fan effect In equation (2.3) the strength of association S_{ji} from a chunk j to a chunk i is used to determine the activation of a chunk i . In the ACT-R theory, the value of S_{ji} is determined by the following rule: If chunk j is not a value in the slots of chunk i and $j \neq i$, then S_{ji} is set to 0. Otherwise S_{ji} is set to:

$$S_{ji} = S - \ln(\text{fan}_j) \quad (2.4)$$

⁵This is called the current context: Usually it means the set of all chunks in all buffers, but there are definitions in literature, that only call the chunk in the goal buffer current context.

2 Description of ACT-R

where fan_j is the number of facts associated to term j [AS00, p. 1042]. In more detail: “ fan_j is the number of chunks in declarative memory in which j is the value of a slot plus one for chunk j being associated with itself” [act12, unit 5, p. 2].

Hence, equation (2.4) states that the associative strength from chunk j to i decreases the more facts are associated to j .

This is due to the *fan effect*: The more facts a person studies about a certain concept, the more time he or she needs to retrieve a particular fact of that concept [AR99, p. 186]. This has been demonstrated in an experiment presented in [AR99], where every participant studied facts about persons and locations like:

- A hippie is in the park.
- A hippie is in the church.
- A captain is in the bank.
- ...

For every person the participants studied either one, two or three facts. Afterwards, they were asked to identify targets, that are sentences they studied, and foils, sentences constructed from the same persons and locations, but that were not in the original set of sentences. Figure ?? represents an example chunk network of the studied sentences (based on [AR99, fig. 1]).

“The term *fan* refers to the number of facts associated with a particular concept” [AR99, p. 186]. In figure ??, some facts are shown with their fan, S_{ji} and B_i values.

The result of the experiment was, that the more facts are associated with a certain concept, the higher was the retrieval time for a particular fact about that concept.

In the ACT-R theory, this result has been integrated in the calculation of the strengths of association: In equation (2.4) the associative strength decreases with the number of associated elements. The value S is a model-dependent constant, but in many models estimated about 2 [ABB⁺04, p. 1042]. Modelers should take notice of setting S high enough that all associative strengths in the model are positive [act12, unit 5, p. 3].

Figure ?? illustrates the activation spreading process.

Latency of Retrieval

As mentioned before, the activation of a chunk affects if the chunk can be retrieved (depending on a threshold and the activation values of the other matching chunks). In addition, activation also has an effect on the retrieval time of a chunk:

$$T_i = F \cdot e^{-A_i} \quad (2.5)$$

where T_i is the *latency* of retrieving chunk i , A_i the activation of this chunk, as defined in equation (2.3), and F the *latency factor*, which is usually estimated to be

$$F \approx 0.35e^\tau \quad (2.6)$$

where τ is the retrieval threshold as mentioned in section 2.3.1, but F can also be set individually by the modeller. Nevertheless, in [ABB⁺04, p. 1042] it is stated that the relationship of the retrieval threshold and the latency factor in equation (2.5) seems to be suitable for a lot of models.

2.3.2 Production Utility

For the production system, there is the subsymbolic concept of *production utilities* to deal with competing strategies. For instance, if a child learns to add numbers, it may have learned different strategies to compute the result: One could be counting with the fingers and the other could be just retrieving a fact for the addition from declarative memory. If the child now has the goal to add two numbers, it somehow has to decide which strategy it will choose, since both strategies match the context.

In ACT-R, production utility is a number attached to each production rule in the system. Just like with activation of chunks, the production rule with the highest utility will be chosen, if there are more than one matching rules. The utilities can be set statically by the modeler, but they can also be learned automatically by practice.

In the current version of the ACT-R theory, a reinforcement learning rule based on the Rescorla-Wagner learning rule [RW72] has been introduced. The utility U_i of a production rule i is defined as:

2 Description of ACT-R

$$U_i(n) = U_i(n-1) + \alpha (R_i(n) - U_i(n-1)) \quad (2.7)$$

where α is the *learning rate* which is usually set around .2 and $R_i(n)$ is the reward the production rule i receives at its n th application [And07, pp. 160–161]. This leads to the utility of a production rule being gradually adjusted to the average reward the rule receives [act12, pp. 6–7].

Usually, rewards can occur at every time and it is not clear which production rule will be strengthened by the reward. In [And07, p. 161] an example is described, where a monkey receives a squirt of juice a second after he presses a button. The question now is, which production rule is rewarded, since between the reward and the firing of a rule there always is a break. In ACT-R, every production that has been fired since the last reward event will be rewarded, but the more time lies between the reward and the firing of the rule, the less is the reward this particular rule receives. The reward for a rule is defined as the amount of external reward minus the time from the rule to the reward. This implies, that the reward has to be measured in units of time, eg., how much time is a monkey willing to spend to get a squirt of juice? [And07, p. 161]

In implementations of ACT-R, rewards can be triggered by the user at any time or can be associated with special production rules that model the successful achievement of a goal (they check, if the current state is a wanted state and then trigger a reward, so every rule that has led to the successful state will be rewarded).

It is important to mention that by the definition of the reward for a production rule, rules also can get a negative reward, if their selection was too long ago. If one wants to penalize all rules since the last reward, a rule with reward 0 can be triggered, which leads to all rules applied before being rewarded with a negative amount of reward.

2.4 Learning

Learning in ACT-R can

[And07, pp. 92–95] [Whi, chapter 4]

3 Constraint Handling Rules

4 Transformation of ACT-R to CHR

After having given a comprehensive but at some time informal overview of the ACT-R theory in chapter 2, this chapter presents a possible implementation of the described concepts of the ACT-R theory in CHR.

For the implementation, some special cases and details that are not exactly defined in theory have to be considered. Hence, some concepts of the theory that are implemented in this work are formalized first. The implementation in form of CHR rules sticks to those formalisms and is often very similar to them.

Additionally, the implementation is described incrementally, ie. first, a very minimal subset of ACT-R is presented that will be refined gradually with the progress of this chapter. In the end, an overview of the actual implementation as a result of this work is given.

Some of the definitions in this chapter result directly from the theory, some of them needed a further analysis of the official ACT-R 6.0 Reference Manual [?] or the tutorials [act12].

4.1 Chunk Stores

Since chunks are the central data-structure of ACT-R, used for representation of declarative knowledge, to exchange information between modules and to state requests, this section first deals with this central part of ACT-R.

4.1.1 Formal Representation of Chunks

In the previous chapters, chunks always have been referred to in a graphical or in a verbose descriptive form. Hence, a formalism to represent chunks in a textual order is given at first. The definition is based on the definition of chunks in the ACT-R implementation.

4 Transformation of ACT-R to CHR

Definition 4.1. A chunk-store Σ is a tuple $(C, E, \mathcal{T}, HasSlot, Isa)$, where C is a set of chunks and E a set of primitive elements, with $C \cap E = \emptyset$. $V = C \cup E$ are the values of Σ and \mathcal{T} a set of chunk-types. A chunk-type $(T, S) \in \mathcal{T}$ is a tuple with a type name T and a set of slots S . The set of all slot-names is S . $HasSlot \subseteq C \times S \times V$ and $Isa \subseteq C \times \mathcal{T}$ are relations and defined as follows:

$c \text{ Isa } T \Leftrightarrow \text{chunk } c \text{ is of type } T$.

$(c, s, v) \in HasSlot \Leftrightarrow v \text{ is the value of slot } s \text{ of } c$. This can also be written as $c \xrightarrow{s} v$ and is spoken “ c is connected to v ” or “ v is in the slot s of c ”.

The function $slots : C \rightarrow S \times V$ is defined as $slots(c) = \{(s, v) | (c, s, v) \in HasSlot\}$ and $slots : \mathcal{T} \rightarrow S$ as $slots((T, S)) = S$.

A chunk-store is type-consistent, if $\forall (c, s, v) \in HasSlot : c \text{ Isa } (T, S) \Rightarrow \exists s' \in S : s = s'$ and $\forall c \in C : c \text{ Isa } (T, S) \Rightarrow \forall s \in S : \exists (c', s', v) \in HasSlot : c = c', s = s'$.

Definition 4.2 (abstract methods of a chunk store). The following methods can be defined over a chunk store $\Sigma = (C, E, \mathcal{T}, HasSlot, Isa)$:

`chunk-type(name slot1 slot2 ... slotn)` adds the type $T = (\text{name}, \{\text{slot}_1, \dots, \text{slot}_n\})$ to the store, ie. $\mathcal{T}' = \mathcal{T} \cup \{T\}$.

`add-chunk(name is a type slot1 val1 ... slotn valn)` adds a new chunk to the store, ie. $C' = C \cup \{\text{name}\}$, $Isa' = Isa \cup (\text{name}, (\text{type}, slots(\text{type})))$ and $HasSlot' = \bigcup_{i=1}^n \text{slot}_i \cup HasSlot$. Note, that due to the expansion of C , the condition that C and E have to be disjoint may be violated. In implementations, there should be a mechanism to restore this condition. Additionally, a valid mechanism to restore type-consistency may be introduced.

FIXME: add other methods. describe empty chunks?

Example 4.1. The addition-fact chunk in figure ?? and its chunk-type are defined as follows:

```
chunk-type(addition-fact arg1 arg2 sum)
chunk(a isa addition-fact arg1 5 arg2 2 sum 7).
```

This leads to the following chunk-store:

$$\begin{aligned}
 &(\{a\}, \{2, 5, 7\}, \\
 &\{(addition - fact, \{arg1, arg2, sum\})\}, \\
 &\{(a, arg1, 5), (a, arg2, 5), (a, sum, 7)\}, \\
 &\{(a, addition - fact)\}).
 \end{aligned}$$

$slots(a) = \{(arg1, 5), (arg2, 2), (sum, 7)\}$ and $slots((addition - fact, \{arg1, arg2, sum\}) = \{arg1, arg2, sum\}$. Hence, the store is type-consistent.

Example 4.2. **FIXME: refer to empty chunks**

4.1.2 Representation of Chunks in CHR

Declarative knowledge is represented as a network of chunks, defined by the two relations *Isa*, specifying the belonging of a chunk to a type, and *HasSlot*, specifying the slot-value pairs of a chunk. Those relations can be translated directly into CHR by defining the following constraints representing the relations and sets:

```

1 :- chr_constraint chunk_type(+).
2 % chunk_type(ChunkTypeName)
3
4 :- chr_constraint chunk_type_has_slot(+, +).
5 % chunk_type_has_slot(ChunkTypeName, SlotName).
```

The `chunk_type/1` constraint represents the set \mathcal{T} of chunk-types in the store, but refers only to the chunk-type names. The set of slots of a chunk-type is specified by the `chunk_type_has_slot/2` constraint¹.

For the chunks:

```

1 :- chr_constraint chunk(+, +).
2 % chunk(ChunkName, ChunkType)
3
4 :- chr_constraint chunk_has_slot(+, +, +).
5 % chunk_has_slot(ChunkName, SlotName, Value)
```

¹For a chunk-type $T \in \mathcal{T}$, with $T = (t, S)$, there exists a `chunk_type(t)` and for every slot $s \in S$ there is a `chunk_type_has_slot(t, s)` in the constraint store.

4 Transformation of ACT-R to CHR

The `chunk/2` constraint represents both the set C of chunks and the Isa relation, since the presence of a constraint `chunk(c, t)` signifies, that chunk c is of a type $T = (t, S)$.

The $HasSlot$ relation is represented by the `chunk_has_slot(c, s, v)` constraint, which really is just a direct translation of an element $(c, s, v) \in HasSlot$.

Simple Implementation of the Default Methods

To implement the methods in definition 4.2, first a data type for chunk specifications has to be introduced. From this specification the correct constraints modeling the chunk-store are added or modified.

The straight-forward definition of a data type for chunk specifications is just to use the specification like in definition 4.2: Since `(name isa type slot_1 val_1 \dots slot_n val_n)` is just a list in LISP and specifies a chunk uniquely, a similar Prolog term can be used:

```
1 :- chr_type chunk_def ---> nil; chunk(any, any, slot_list).
2 :- chr_type list(T) ---> []; [T | list(T)].
3 :- chr_type slot_list == list(pair(any,any)). % a list of slot-value pairs
4 :- chr_type pair(T1,T2) ---> (T1,T2).
```

This definition states that a chunk is either `nil`, ie. an empty chunk, or a term `chunk(Name, Type, SVP)`, where SVP is a list of slot-value pairs. This is the direct translation of the chunk-specification used in the definition, amended by the `nil` construct, that may be needed for later purposes.

The default methods can be implemented as follows:

Listing 4.1: rules for `add_chunk`

FIXME: add very simple solution

Listing 4.2: rules for `add_chunk_type`

```
1 add_chunk_type(CT, []) <=>
2   chunk_type(CT).
3 add_chunk_type(CT, [S|Ss]) <=>
4   chunk_type_has_slot(CT, S),
5   add_chunk_type(CT, Ss).
```

FIXME: add duplicate handling

Checking Type-Consistency

FIXME: missing

4.2 Procedural Module

The part of the system, where the computations are performed, is the procedural module. It is the central component, that holds all the production rules, the working memory (in the buffer system) and organizes communication between modules (through buffers and requests). In the following, all of those subcomponents of the procedural module are described.

4.2.1 Buffer System

The buffer system can be regarded as a chunk-store, that is enhanced by buffers. A buffer can hold only one chunk at a time. The procedural module has a set B of buffers, a chunk-store Σ and a relation between the buffers and the chunks in Σ .

Definition 4.3 (buffer system). *A buffer system is a tuple $(B, \Sigma, Holds)$, where B is a set of buffers, $\Sigma = (C, E, \mathcal{T}, HasSlot, Isa)$ a type-consistent chunk-store and $Holds \subseteq B \times (C \cup \{\text{nil}\})$ a unique and complete relation, that assigns every buffer at most one chunk that it holds. If a buffer b is empty, ie. it does not hold a chunk, then $(b, \text{nil}) \in Holds$.*

A buffer system is consistent, if every chunk that appears in $Holds$ is a member of C and Σ is consistent.

A buffer system is clean, if its chunk-store only holds chunks which appear in $Holds$.

For the implementation of a buffer system, the code of a chunk-store can be extended by a `buffer/2` constraint, that encodes the set B and the relation $Holds$ at once, since the relation is complete by definition².

² $\forall b \in B \exists c \in (C \cup \{\text{nil}\}) : (b, c) \in Holds$

4 Transformation of ACT-R to CHR

Destructive Assignment and Consistency

The demand of *Holds* being unique is a form of destructive assignment as described in [Frü09, p. 32], ie. if a new chunk is assigned to a buffer, the old `buffer` constraint is removed and a new `buffer` constraint is introduced, holding the new chunk:

```
1 set_buffer(b, c) \ buffer(b, _) <=> buffer(b, c).
```

This rule ensures that only one `buffer` exists for each buffer in *B*.

In addition, if a new chunk is introduced in a buffer, it also has to be present in the chunk-store, since the production system relies on the knowledge about the chunks in its buffers and chunks are essentially defined by their slots (*consistency property* in definition 4.3). Hence, every time a chunk is stored in a buffer, the `add_chunk` method described in definition 4.2 has to be called. This process is discussed later when talking about buffer requests in section ??.

Buffer States

Another formal detail of the buffer system is that buffers can have various states.

4.2.2 Production Rules

grammar

```
1 production-definition ::= p-name {doc-string} condition* ==> action*
2 p-name ::= a symbol that serves as the name of the production for reference
3 doc-string ::= a string which can be used to document the production
4 condition ::= [ buffer-test | query | eval | binding | multiple-value-binding ]
5 action ::= [ buffer-modification | request | buffer-clearing | modification-request ]
6 binding | multiple-value-binding | output | !stop! ]
7 buffer-test ::= =buffer-name> isa chunk-type slot-test*
8 buffer-name ::= a symbol which is the name of a buffer
9 chunk-type ::= a symbol which is the name of a chunk-type in the model
10 slot-test ::= {slot-modifier} slot-name slot-value
11 slot-modifier ::= [= | - | < | > | <= | >=]
12 slot-name ::= a symbol which names a possible slot in the specified chunk-type
```



```

13 slot-value ::= a variable or any Lisp value
14 query ::= ?buffer-name> query-test*
15 query-test ::= {-} queried-item query-value
16 queried-item ::= a symbol which names a valid query for the specified buffer
17 query-value ::= a bound-variable or any Lisp value
18 buffer-modification ::= =buffer-name> slot-value-pair*
19 slot-value-pair ::= slot-name bound-slot-value
20 bound-slot-value ::= a bound variable or any Lisp value
21 request ::= +buffer-name> [direct-value | isa chunk-type request-spec*]
22 request-spec ::= {slot-modifier} [slot-name | request-parameter] slot-value
23 request-parameter ::= a Lisp keyword naming a request parameter provided by the buffer sp
24 direct-value ::= a variable or Lisp symbol
25 buffer-clearing ::= -buffer-name>
26 modification-request ::= +buffer-name> slot-value-pair*
27 buffer-overwrite ::= =buffer-name> direct-value
28 variable ::= a symbol which starts with the character =
29 eval ::= [!eval! | !safe-eval!] form
30 binding ::= [!bind! | !safe-bind!] variable form
31 +
32 multiple-value-binding ::= !mv-bind! (variable ) form
33 output ::= !output! [ output-value | ( format-string format-args*) | (output-value*)]
34 output-value ::= any Lisp value or a bound-variable
35 format-string ::= a Lisp string which may contain format specific parameter processing ch
36 format-args ::= any Lisp values, including bound-variables, which will be processed by th
37 format-string
38 bound-variable
39 ::= a variable which is used in the buffer-test conditions of the production (including
40 variable which names the buffer that is tested in a buffer-test or dynamic-buffer-test) c
41 an explicit binding in the production
42 form ::= a valid Lisp form

```

4.3 Modular Organization

interface for requests

4.4 Declarative Module

uses chunks as defined in section ??

4.4.1 Retrieval Requests

interface module request

4.5 Timing in ACT-R

scheduling, define recognize-act-cycle in detail

4.5.1 Priority Queue

4.6 Subsymbolic Layer

4.6.1 Activation of Chunks

4.6.2 Production Utility

5 Compiler

6 Example Models

6.1 The Counting Model

6.2 The Addition Model

6.3 The Semantic Model

6.4 The Fan Model

simplified version of fan model

7 Conclusion

7.1 Inventory: What does already work?

7.2 Future Work

A Source Codes

In diesem Anhang sind einige wichtige Quelltexte aufgeführt.

```
1 :- use_module(library(chr)).  
2  
3 % just a test  
4  
5 a(X) <=> check(X) | b.  
6  
7 check(13).  
8 check(X) :-  
9     X <10.
```


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Erklärung

Ich erkläre, dass ich die Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Ulm, den

Daniel Gall