Unit 1: Introduction to ACT-R

ACT-R is a cognitive architecture. It is a theory of the structure of the brain at a level of abstraction that explains how it achieves human cognition. That theory is instantiated in the ACT-R software which allows one to create models which may be used to explain performance in a task and also to predict performance in other tasks. This tutorial will describe how to use the ACT-R software for modeling and provide some of the important details about the ACT-R theory. Detailed information on the ACT-R theory can be found in the paper "An integrated theory of the mind", which is available on the ACT-R website and also in the book "How Can the Human Mind Occur in the Physical Universe?". More information on the ACT-R software can be found in the reference manual which is included in the docs directory of the ACT-R software distribution.

The goals of this unit are to introduce the basic components of the ACT-R architecture and show how those components are used to create and run a model in the ACT-R software.

1.1 Knowledge Representations

There are two types of knowledge representation in ACT-R -- **declarative** knowledge and **procedural** knowledge. Declarative knowledge corresponds to things we are aware we know and can usually describe to others. Examples of declarative knowledge include "George Washington was the first president of the United States" and "An atom is like the solar system". Procedural knowledge is knowledge which we display in our behavior but which we are not conscious of. For instance, no one can describe the rules by which we speak a language and yet we do. In ACT-R, declarative knowledge is represented in structures called **chunks** and procedural knowledge is represented as rules called **productions**. Chunks and productions are the basic building blocks of an ACT-R model.

1.1.1 Chunks in ACT-R

In ACT-R, elements of declarative knowledge are called **chunks**. Chunks represent knowledge that a person might be expected to have when they solve a problem. A chunk is a collection of attributes and values. The attributes of a chunk are called **slots**. Each slot in a chunk has a single value. A chunk also has a name which can be used to reference it, but that name is only a convenience for using the ACT-R software and is not considered to be a part of the chunk itself. Below are some representations of chunks that encode the facts that *the dog chased the cat* and that *4+3=7*. The chunks are displayed as a name and then slot and value pairs. The name of the first chunk is **action023** and its slots are **verb**, **agent,** and **object**, which have values of chase, dog, and cat respectively.   The second chunk is named **fact3+4** and its slots are **addend1**, **addend2**, and **sum**, with values three, four, and seven.

```
Action023
    verb chase
    agent dog
    object cat
```

```
Fact3+4
    addend1 three
    addend2 four
    sum seven
```

1.1.2 Productions in ACT-R

A production is a statement of a particular contingency that controls behavior. They can be represented as if-then rules and some examples might be:

IF the goal is to classify a person

　 and he is unmarried

THEN classify him as a bachelor

IF the goal is to add two digits d1 and d2 in a column

　 and d1 + d2 = d3

THEN create a goal to write d3 in the column

The condition of a production (the IF part) consists of a conjunction of features which must be true for the production to apply. The action of a production (the THEN part) consists of the actions the model should perform when the production is selected and used. The above are informal English specifications of productions. They give an overview of when the productions apply and what actions they should perform, but do not specify sufficient detail to actually implement a production in ACT-R. You will learn the specific syntax for creating productions in ACT-R later in this unit.

1.2 The ACT-R Architecture

The ACT-R architecture consists of a set of **modules**. Each module performs a particular cognitive function and operates independently of other modules. We will introduce three modules in this unit and describe their basic operations. Later units will provide more details on the operations of these modules and also introduce other modules.

The modules communicate through an interface we call a **buffer**. Each module may have any number of buffers for communicating with other modules. A buffer relays requests to its module to perform some action, it responds to queries about the status of the module and the buffer itself,

and it can hold one chunk at a time which is usually placed into the buffer as the result of an action which was requested. The chunk in a buffer is available for any module to see and modify and effectively works like a scratch-pad for creating and modifying chunks.

1.2.1 Goal Module

The goal module is the simplest of the modules in ACT-R. It has one buffer named **goal** which is used to hold a chunk which contains the current control information the model needs for performing its current task. The only request to which the module responds is for the creation of a new goal chunk. It responds to the request by immediately creating a chunk with the information contained in the request and placing it into the **goal** buffer.

1.2.2 Declarative Module

The declarative module stores all of the chunks which represent the declarative knowledge the model has which is often referred to as the model's declarative memory. It has one buffer named **retrieval**. The declarative module responds to requests by searching through declarative memory to find the chunk which best matches the information specified in the request and then placing that chunk into the **retrieval** buffer. In later units we will cover that process in more detail to describe how it determines the best match and how long the process takes. For the models in this unit, there will never be more than one chunk which matches the request and the time cost will be fixed in the models at 50 milliseconds per request.

The declarative memory in the model consists of the chunks which are placed there initially by the modeler when defining the model and the knowledge which it learns as it runs. The learned knowledge is collected from the buffers of all of the modules. The declarative module monitors all of the buffers, and whenever a chunk is cleared from one of them the declarative module stores that chunk for possible later use.

1.2.3 Procedural Module

The procedural module holds all of the productions which represent the model's procedural knowledge. It does not have a buffer of its own, and unlike other modules the procedural module does not take requests for actions. Instead, it is constantly monitoring the activity of all the buffers looking for patterns which satisfy the condition of some production. When it finds a production which has its condition met then it will execute the actions of that production, which we refer to as "firing" the production. Only one production can fire at a time and it takes 50 milliseconds from the time the production was matched to the current state until the actions happen. In later units we will look at what happens if more than one production matches at the same time, but for this unit all of the productions in the models will have their conditions specified so that at most one will match at any point in time.

1.2.4 Overview

These three modules are used in almost every model which is written in ACT-R, and older versions of ACT-R consisted entirely of just these three components. Here is a diagram showing how they fit together in the architecture with the rectangles representing the modules and the ovals representing the buffers:
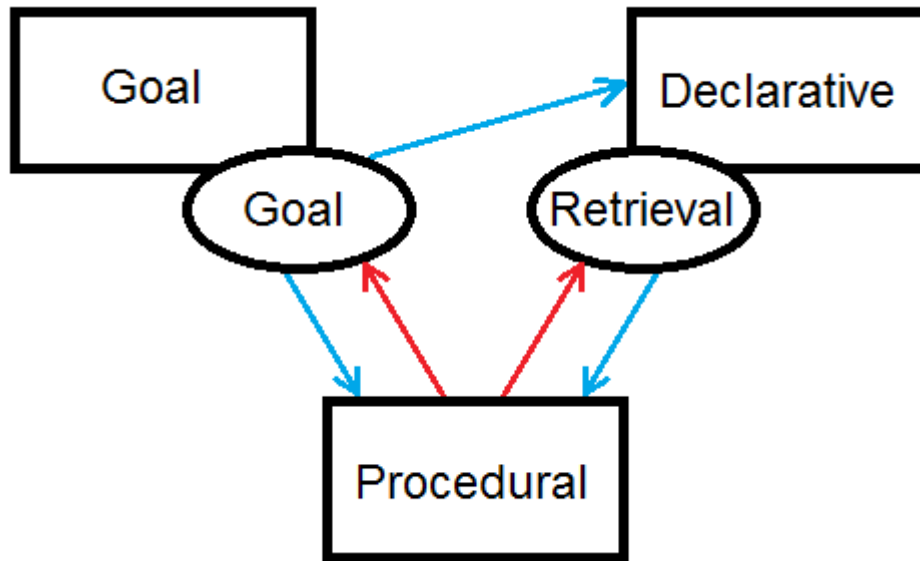
The blue arrows show which modules read the information from another module's buffer, and the red arrows show which modules make requests to another module's buffer or directly modify the chunk it contains. As we introduce new modules and buffers in the tutorial, each of the buffers will have the same interface as shown for the goal buffer -- both the procedural and declarative modules will read the buffer information and the procedural module will modify and make requests to the buffer.

1.3 ACT-R Software and Models

Now that we have described the basic components in ACT-R, we will step back and describe the ACT-R software and how one creates and runs a model using it. This tutorial is written for version 7.12 (or newer) of the ACT-R software. Unlike previous versions, version 7.12 of the software is distributed primarily as applications and the tutorial instructions will assume that the user is running one of those applications, but like previous versions the source code is available for those that prefer to run from sources. The main ACT-R software is implemented in the ANSI Common Lisp programming language, but it is not necessary to know how to program in Lisp to be able to use ACT-R because it is essentially its own language. In prior versions of the software it was necessary to interact with ACT-R through Lisp code, and one had to write Lisp code to build experiments or other tasks for the model to perform. However, starting with version 7.6, ACT-R provides a remote interface that can be used to interact with ACT-R from essentially any programming language, and the tutorial materials include a Python module (in the Python use of the term module not the ACT-R use as a cognitive component of the architecture) which provides functions for accessing ACT-R through that remote interface. Using that Python module, all of the tasks for the models in the tutorial are implemented in Python as well as the original Lisp implementations of the tasks, and either version can be used with the models of the tutorial.

1.3.1 Starting ACT-R

To run the ACT-R software you need to run the startup script named *run-act-r* that is included with the standalone version for your operating system (versions are available for Linux, MacOS X, or Windows). That will open two windows for the ACT-R software. The one titled "ACT-R" is an interactive Lisp session which contains the main ACT-R system and can be used to interact with ACT-R directly. The other window, titled "Control Panel", contains a set of GUI tools written in the Tcl/Tk programming language and is called the ACT-R Environment. The ACT-R Environment is an optional set of tools for interacting with the ACT-R system and the use of some of those tools will be described during the tutorial (more information on the Environment tools can be found in the Environment's manual included in the docs directory of the software). You may close the ACT-R Environment window if you do not wish to use those tools (note however that for this unit the Environment tools are necessary and it should not be closed). Closing the ACT-R window will exit the software.

For this unit there are no tasks for the models to interact with, and all the interaction with the software can be done through the ACT-R Environment. For that reason, we will not describe how to use the Python module yet since there is no need for it, but it will be described in the next unit which includes tasks for the tutorial models to perform.

1.3.2 Interacting with Lisp

Although it is not necessary to use the Lisp interface for ACT-R, it can be convenient and some familiarity with Lisp syntax can be helpful since the syntax for creating ACT-R models is based on Lisp syntax. Lisp is an interactive language and provides a prompt at which the user can issue commands and evaluate code. The prompt in the ACT-R software window is the "?" character. To evaluate (also sometimes referred to as "calling") a command in Lisp at the prompt requires placing it between parentheses along with any parameters which it requires separated by whitespace and then hitting enter or return. As an example, to evaluate the command to add the numbers 3 and 4 requires calling the command named "+" with those parameters. That means one would type this at the prompt:

```
(+ 3 4)
```

and then hit the enter or return key. The system will then print the result of evaluating that command and display a new prompt:

```
? (+ 3 4)
7
?
```

One minor issue to note is that sometimes the output from the ACT-R system will overwrite the prompt character and it will not be visible in the ACT-R window. When that happens you can still evaluate commands by entering them at the bottom of the window and pressing enter or return.

1.3.3 ACT-R models

An ACT-R model is a simulated cognitive agent. A model is typically written in a text file that contains the ACT-R commands that specify how the model works, and that model file can be opened and edited in any application that can operate on text files. Because the ACT-R model syntax is based on Lisp syntax using an editor which provides additional support for Lisp formatting, like matching parentheses and automatic indenting, can be useful but is not necessary. There is a very simple text editor included with the ACT-R Environment tools which will do parenthesis matching, but beyond that it is a very limited text editor.

As we progress through the tutorial we will describe the ACT-R commands which one can use to create models. Later in this unit we will introduce the commands for initializing a model and creating the knowledge structures described above (chunks and productions).

1.3.4 Loading a model

To use an ACT-R model file it must be "loaded" into ACT-R. There are many ways to do so, but for this unit we will simply use the button in the ACT-R Environment labeled "Load ACT-R code". In the next unit we will show how to load a model using an ACT-R command that can be called from the Lisp prompt or from an external connection, like the Python module. When the model file is loaded, the commands it contains are evaluated in order from the top down.

1.3.5 Running a model

Once a model has been loaded, you can run it. Models that do not interact with a task can typically be run by just calling the ACT-R **run** command. The **run** command requires one parameter, which is the maximum length of simulated time to run the model measured in seconds. Again, for this unit we will be using the tool in the ACT-R Environment instead of using the command itself. That tool is the "Run" button in the Environment and the text entry box to its right is where the time to run the model can be entered. The default time in that box is 10.0 which means pressing the "Run" button will run the model for up to 10 simulated seconds.

In later units, where the models will be interacting with various tasks, just pressing the "Run" button or calling the **run** command may not be sufficient because one might also have to run the task itself. When that is the case the tutorial will describe what is necessary to run the model and the task, and there is an additional text included with each unit that describes how the tasks are implemented and the ACT-R commands involved (those are the texts with a name that ends with "_code").

1.4 Creating an ACT-R Model

Creating an ACT-R model requires writing the text file which contains the ACT-R commands to specify the details of the model and the initial knowledge it contains. Also, in addition to the model's details, one often includes commands for controlling the general state of the ACT-R system itself.

1.4.1 ACT-R control commands

When creating an ACT-R model, there are two ACT-R commands for controlling the system which will almost always occur in the model file, and we will describe those commands first.

1.4.1.1 clear-all

The **clear-all** command will usually occur at the top of every model file. This command requires no parameters and tells ACT-R that it should remove any models which currently exist and return ACT-R to its initial state. It is not necessary to call **clear-all** in a model file, but unless one is planning on running multiple models together it is strongly recommended that it occur as the first command to make sure that the model starts with the system in a properly initialized state.

1.4.1.2 define-model

The **define-model** command is how one actually creates an ACT-R model. Within the call to **define-model** one specifies a name for the model and then includes all of the calls to ACT-R commands that will provide the initial conditions and knowledge for that model. When the model file is loaded, define-model will create the model with the conditions specified, and then whenever ACT-R is reset that model will be returned to that same initial state.

1.4.2 Chunk-Types

Before describing the commands for creating the model's initial knowledge with chunks and productions, we will first describe an additional component of the software which can be useful when creating a model. There is an optional capability available in the ACT-R software called a **chunk-type**. A chunk-type is a way for the modeler to specify categories for the knowledge in the model by indicating a set of slots which will be used together in the creation and testing of chunks. A chunk-type consists of a name for the chunk-type and a set of slot names. That chunk-type name may then be used as a declaration when creating chunks and productions in the model.

The command for creating a chunk type is called **chunk-type**. It requires a name for the new chunk-type to create and then any number of slot names. The general chunk-type specification looks like this:

```
(chunk-type type-name slot-name-1 slot-name-2 … slot-name-n)
```

and here are some examples which could have been used in a model which created the example chunks shown earlier:

```
(chunk-type action verb agent object)
(chunk-type addition-fact addend1 addend2 sum)
```

The first creates a chunk-type named action which includes the slots verb, agent, and object. The other creates a chunk-type named addition-fact with slots addend1, addend2, and sum.

It is important to note that using a chunk-type declaration does not directly affect the operation of the model itself – the chunk-type is not a component of the ACT-R architecture. They exist in the software to help the modeler specify the model components. Creating and using meaningful chunk-types can make a model easier to read and understand. They also allow the ACT-R software to verify that the specification of chunks and productions in a model is consistent with the chunk-types that were created for that model which allows it to provide warnings when inconsistencies or problems are found relative to the chunk-types which are specified.

Although chunk-types are not required when writing an ACT-R model, most of the models in the tutorial will be written with chunk-type declarations included, and using chunk-types is strongly recommended.

1.4.3 Creating Chunks

The command to create a set of chunks and place those chunks into the model's declarative memory is called **add-dm**. It takes any number of chunk specifications as its arguments. As an example, we will show the chunks from the **count** model included with the tutorial that will be described in greater detail later in this unit. First, here are the chunk-type specifications used in that model:

```
(chunk-type count-order first second)
(chunk-type count-from start end count)
```

and here is the specification of the initial chunks which are placed into that model's declarative memory:

```
(add-dm
   (b ISA count-order first 1 second 2)
   (c ISA count-order first 2 second 3)
   (d ISA count-order first 3 second 4)
   (e ISA count-order first 4 second 5)
   (f ISA count-order first 5 second 6)
   (first-goal ISA count-from start 2 end 4))
```

Each chunk for **add-dm** is specified in a list – a sequence of items enclosed in parentheses. The first element of the list is the name of the chunk. The name may be anything which is not already used as the name of a chunk as long as it starts with an alphanumeric character and is a valid Lisp symbol (essentially a continuous sequence of characters which does not contain any of the symbols: period, comma, single quote, double quote, back quote, left or right parenthesis, backslash, or semicolon). In the example above the names are **b**, **c**, **d**, **e**, **f**, and **first-goal**. The purpose of the name is to provide a way for the modeler to refer to the chunk. The name is not considered to be a part of the chunk, and it can in fact be omitted, which will result in the system automatically generating a unique name for the chunk.

The next component of the chunk specification is the optional declaration of a chunk-type to describe the chunk being created. That consists of the symbol **isa** followed by the name of a chunk-type. Note that here we have capitalized the isa symbol to help distinguish it from the actual slots of the chunk, but that is not necessary and generally the symbols and names used in ACT-R commands are not case sensitive.

The rest of the chunk specification is pairs of a slot name and a value for that slot. The slot-value pairs can be specified in any order and the order does not matter. When a chunk-type declaration is provided, it is not necessary to specify a value for every slot indicated in that chunk-type, but if a slot which is not specified in that chunk-type is provided ACT-R will generate a warning to indicate the potential problem to the modeler.

1.4.4 Creating Productions

As indicated above, each production is a condition-action rule. Those rules are used by the procedural module to monitor the buffers of all the other modules to determine when to perform actions. The condition specifies tests for the contents of the buffers as well as the general state of the buffers and their modules. The action of a production specifies the set of operations to perform when the production is fired, and will consist of changes to be made to the chunks in buffers along with new requests to be sent to the modules.

The command for creating a production in ACT-R is **p**, and the general format for creating a production is:

```
(p Name "optional documentation string"
  buffer tests
==>
  buffer changes and requests
)
```

Each production must have a unique name and may also have an optional documentation string to describe it. That is followed by the condition for the production. The *buffer tests* in the condition of the production are patterns to match against the current buffers' contents and queries of the buffers for buffer and module state information. The condition of the production is separated from the action of the production by the three character sequence `==>`. The production's action consists of any buffer changes and requests which the production will make.

In separate subsections to follow we will describe the syntax involved in specifying the condition and the action of a production. In doing so we will use an example production that counts from one number to the next based on a chunk which has been retrieved from the model's declarative memory. It is similar to those used in the example models for this unit, but is slightly simpler than they are for example purposes. Here is the specification of the chunk-types used in the example production:

```
(chunk-type count-order first second)
(chunk-type count state number)
```

Here is the example production, which is named counting-example:

```
(P counting-example
   "example production for counting in tutorial unit 1 text"
  =goal>
   ISA       count
   state     incrementing
   number    =num1
  =retrieval>
   first     =num1
   second    =num2
==>
  =goal>
   ISA       count
   number    =num2
  +retrieval>
   ISA       count-order
   first     =num2
)
```

It is not necessary to space the production definition out over multiple lines or indent the components as shown above. It could be written on one line with only a single space between each symbol and result in the creation of the same production. Because of that, the condition of the production is also often referred to as the left-hand side (or LHS) and the action as the right-hand side (or RHS), because of their positions relative to the **==>** separator. However, since adding additional whitespace characters between the symbols does not affect the definition of productions, they are typically written spaced out over several lines to make them easier to read.

The symbols used in the production definition are also not case sensitive. The symbol ISA is only capitalized for emphasis in the example and it could have been written as isa, Isa, or any other combination of capital and lowercase letters with the same result.

1.4.4.1 Production Condition: Buffer Pattern Matching

The condition of the counting-example production specifies a pattern to match to the **goal** buffer and a pattern to match to the **retrieval** buffer. A buffer pattern begins with a symbol that starts with the character "=" and ends with the character ">". Between those characters is the name of the buffer to which the pattern is applied. Thus, the symbol =goal> indicates a pattern used to test the chunk in the **goal** buffer and the symbol =retrieval> indicates a pattern to test the chunk in the **retrieval** buffer. For a production's condition to match, the first thing that must be true is that there be a chunk in each of the buffers being tested. Thus, if there is no chunk in either the **goal** or **retrieval** buffer, often referred to as the buffer being empty or cleared, this production cannot match.

After indicating which buffer to test, an optional declaration may be made using the symbol isa and the name of a chunk-type to provide a declaration of the set of slots which are being used in the test. In the example production, the **goal** buffer pattern includes a declaration that the slots being tested are from the count chunk-type, but the **retrieval** buffer pattern does not declare a type for the set of slots specified. It is recommended that one create chunk-types and use the isa declarations when writing productions, but this one has been omitted for demonstration purposes. The important thing to remember is that the isa declaration is not a part of the pattern to be tested – it is only a declaration to allow the ACT-R software to verify that the slots used in the pattern are consistent with the chunk-type indicated.

The remainder of the pattern consists of slot tests to perform using the chunk in the specified buffer. A slot test consists of an optional modifier (which is not used in any of the tests in this example production), the name of a slot for the chunk in the buffer, and a specification of the value that slot of the chunk in the buffer must have. The value may be specific as a constant value, a variable, or the Lisp symbol **nil**.

Here is the **goal** buffer pattern from the example production again for reference:

```
=goal>
    ISA        count
    state      incrementing
    number     =num1
```

The first slot test in the pattern is for a slot named **state** with a constant value of **incrementing**. Therefore for this production to match, the chunk in the **goal** buffer must have a slot named **state** which has the value **incrementing**. The next slot test in the pattern involves the slot named **number** and a variable value.

The "=" prefix on a symbol in a production is used to indicate a variable. The name of the variable can be any symbol, and it is recommended that the variable names be chosen to help make the production easier for a person reading it to understand. Variables are used in a production to generalize the condition and action, and they have two basic purposes. In the condition, variables can be used to compare the values in different slots, for instance that they have the same value or different values, without needing to know all the possible values those slots could have. The other purpose for a variable is to copy a value from a slot specified in the condition to another slot specified in the action of the production.

There are two properties of variables used in productions which are important. Every slot tested with a variable in the condition must exist in the chunk in the buffer for the pattern to match. Also, a variable is only meaningful within a specific production -- using the same variable name in different productions does not create any relation between those productions.

Given that, we could describe this production's test for the **goal** buffer like this:

There must be a chunk in the goal buffer. It must have a slot named state with the value incrementing, and it must have a slot named number whose value we will refer to using the variable =num1.

Now, we will look at the **retrieval** buffer's pattern in detail:

```
=retrieval>
   first        =num1
   second       =num2
```

The first slot test it has tests the slot named **first** with the variable **=num1**. Since the variable **=num1** was also used in the **goal** buffer test, this is testing that the **first** slot of the chunk in the **retrieval** buffer has the same value as the **number** slot of the chunk in the **goal** buffer. The other slot test for the **retrieval** buffer is for the slot named **second** using a variable named **=num2**.

Therefore, the test for the **retrieval** buffer can be described as:

There must be a chunk in the retrieval buffer. It must have a slot named first which has the same value as the slot named number of the chunk in the goal buffer, and it must have a slot named second whose value we will refer to using the variable =num2.

There is one other detail to note about the buffer pattern tests on the LHS of a production. Notice that the specification of a buffer pattern begins with the character "=" which is also used to indicate a variable in a production. The start of a buffer pattern is also specifying a variable using the name of the buffer. In this production that would be the variables =goal and =retrieval. Those variables will refer to the chunk that is in the **goal** buffer and the chunk that is in the **retrieval** buffer respectively, and those variables can be used just like any other variable to test a value in a slot or to place that chunk into a slot as an action.

This example production did not include all of the possible items which one may need in writing the condition for a production, but it does cover the basics of the pattern matching applied to chunks in buffers. We will describe how one queries the buffer and module state later in this unit, and additional production condition details will be introduced in future units.

1.4.4.2 Production Action

The action of a production consists of a set of operations which affect the buffers. Here is the RHS from the example production again:

```
=goal>
  ISA       count
  number    =num2
 +retrieval>
  ISA       count-order
```

```
  first     =num2
```

The RHS of a production is specified much like the LHS with actions to perform on particular buffers. To indicate a particular action to perform with a buffer a symbol is used which starts with a character that indicates the action to take, followed by the name of a buffer, and then the character ">". That is followed by an optional chunk-type declaration using isa and a chunk-type name and then the specification of slots and values to detail the action to perform. There are five different operations that can be performed with a buffer. The three most common will be described in this unit. The other operations will be described later in the tutorial.

1.4.4.2.a Buffer Modifications, the = action

If the buffer name is prefixed with the character "=" then the action will cause the production to immediately modify the chunk currently in that buffer. Each slot specified in a buffer modification action indicates a change to make to the chunk in the buffer. If the chunk already has such a slot its value is changed to the one specified. If the chunk does not currently have that slot then that slot is added to the chunk with the value specified.

Here is the action for the **goal** buffer from the example production:

```
  =goal>
   ISA       count
   number    =num2
```

It starts with the character "=" therefore this is a modification to the buffer. It will change the value of the **number** slot of the chunk in the **goal** buffer (since we know that it has such a slot because it was tested in the condition of the production) to the value referred to by the variable =**num2** (which is the value that the **second** slot of the chunk in the **retrieval** buffer had in the condition). This is an instance of a variable being used to copy a value from one slot to another.

1.4.4.2.b Buffer Requests, the + action

If the buffer name is prefixed with the character "+", then the action is a request to that buffer's module, and we will often refer to such an action as a "*buffer* request" where *buffer* is the name of the buffer indicated e.g. a retrieval request or a goal request. Typically this results in the module replacing the chunk in the buffer with a different one, but not all modules handle requests the same way. As was noted above, the goal module handles requests by creating new chunks and the declarative module uses the request to find a matching chunk in the model's declarative memory to place into the buffer. In later units of the tutorial we will describe modules that perform perceptual and motor actions in response to requests.

Here is the retrieval request from the example production:

```
  +retrieval>
    ISA            count-order
```

```
    first        =num2
```

It is asking the declarative module to find a chunk that has a slot named **first** that has the same value as =**num2**. If such a chunk exists in the model's declarative memory it will be placed into the **retrieval** buffer.

1.4.4.2.c Buffer Clearing, the - action

A third type of action that can be performed with a buffer is to explicitly clear the chunk from the buffer. This is done by placing the "-" character before the buffer name in the action. Thus, this action on the RHS of a production would clear the chunk from the **retrieval** buffer:

```
  -retrieval>
```

Clearing a buffer occurs immediately and results in the buffer being empty and the declarative module storing the chunk which was in the buffer in the model's declarative memory.

1.4.4.2.d Implicit Clearing

In addition to the explicit clearing action one can make, there are situations which will implicitly clear a buffer. Any buffer request with a "+" action will also cause that buffer to be cleared. Therefore, the retrieval request from the example production will also result in the **retrieval** buffer being automatically cleared at the time the request is made. Later units will describe other places where implicit buffer clearing will occur.

1.5 The Count Model

The first model we will run is a simple one that counts up from one number to another, for example it will count up from 2 to 4 -- 2,3,4. It is included with the tutorial files for unit 1 in the file named "count.lisp". You should now start the ACT-R software if you have not done so already, and then load the count model by pressing the "Load ACT-R code" button on the ACT-R Environment Control Panel and selecting the "count.lisp" file.

When you do that, you should see a window open up which says "Successful Load", with no other text in the window. You should press the "Ok" button on that window to continue. If there had been any problems when loading the file then details about those issues would have been shown in that window.

Now you should run the model by pressing the "Run" button on the ACT-R Environment Control Panel. That will run the model for up to 10 seconds, since the default time shown next to the button is 10.0. When you do that, you should see the following output in the ACT-R window:

```
    0.000   GOAL                    SET-BUFFER-CHUNK GOAL FIRST-GOAL NIL
    0.000   PROCEDURAL              CONFLICT-RESOLUTION
    0.000   PROCEDURAL              PRODUCTION-SELECTED START
```

```
        0.000   PROCEDURAL              BUFFER-READ-ACTION GOAL
        0.050   PROCEDURAL              PRODUCTION-FIRED START
        0.050   PROCEDURAL              MOD-BUFFER-CHUNK GOAL
        0.050   PROCEDURAL              MODULE-REQUEST RETRIEVAL
        0.050   PROCEDURAL              CLEAR-BUFFER RETRIEVAL
        0.050   DECLARATIVE             start-retrieval
        0.050   PROCEDURAL              CONFLICT-RESOLUTION
        0.100   DECLARATIVE             RETRIEVED-CHUNK C
        0.100   DECLARATIVE             SET-BUFFER-CHUNK RETRIEVAL C
        0.100   PROCEDURAL              CONFLICT-RESOLUTION
        0.100   PROCEDURAL              PRODUCTION-SELECTED INCREMENT
        0.100   PROCEDURAL              BUFFER-READ-ACTION GOAL
        0.100   PROCEDURAL              BUFFER-READ-ACTION RETRIEVAL
        0.150   PROCEDURAL              PRODUCTION-FIRED INCREMENT
2
        0.150   PROCEDURAL              MOD-BUFFER-CHUNK GOAL
        0.150   PROCEDURAL              MODULE-REQUEST RETRIEVAL
        0.150   PROCEDURAL              CLEAR-BUFFER RETRIEVAL
        0.150   DECLARATIVE             start-retrieval
        0.150   PROCEDURAL              CONFLICT-RESOLUTION
        0.200   DECLARATIVE             RETRIEVED-CHUNK D
        0.200   DECLARATIVE             SET-BUFFER-CHUNK RETRIEVAL D
        0.200   PROCEDURAL              CONFLICT-RESOLUTION
        0.200   PROCEDURAL              PRODUCTION-SELECTED INCREMENT
        0.200   PROCEDURAL              BUFFER-READ-ACTION GOAL
        0.200   PROCEDURAL              BUFFER-READ-ACTION RETRIEVAL
        0.250   PROCEDURAL              PRODUCTION-FIRED INCREMENT
3
        0.250   PROCEDURAL              MOD-BUFFER-CHUNK GOAL
        0.250   PROCEDURAL              MODULE-REQUEST RETRIEVAL
        0.250   PROCEDURAL              CLEAR-BUFFER RETRIEVAL
        0.250   DECLARATIVE             start-retrieval
        0.250   PROCEDURAL              CONFLICT-RESOLUTION
        0.250   PROCEDURAL              PRODUCTION-SELECTED STOP
        0.250   PROCEDURAL              BUFFER-READ-ACTION GOAL
        0.300   DECLARATIVE             RETRIEVED-CHUNK E
        0.300   DECLARATIVE             SET-BUFFER-CHUNK RETRIEVAL E
        0.300   PROCEDURAL              PRODUCTION-FIRED STOP
4
        0.300   PROCEDURAL              CLEAR-BUFFER GOAL
        0.300   PROCEDURAL              CONFLICT-RESOLUTION
        0.300   ------                  Stopped because no events left to process
```

This output is called the trace of the model. Each line of the trace represents one event that occurred during the running of the model. Each event shows the time in seconds at which it happened, the ACT-R module that generated the event, and some details describing the event. Any output generated by the model is also shown in the trace. The level of detail provided in the trace can be changed to see more or less information as needed, and this model is set to show the most information possible. How to change the amount of detail shown in the trace is described in the unit 1 code description document, named "unit1_code".

You should now open the count model in a text editor (if you have not already) to begin looking at how the model is specified. Since we will not be editing the file, the simple editor provided by the ACT-R Environment is sufficient to see the model definition, and you can use that by pressing the "Open File" button on the Control Panel.

The first two commands used in the model file are **clear-all** and **define-model** as described above, and the rest of the file contains the model definition within the **define-model** call.

The first item in the model definition is a call to the **sgp** command which is used to set parameters for the model. We will not describe that here, but it is covered in the code description document. The rest of the model definition contains the chunks and productions for performing this task, and we will look at those in detail.

1.5.1 Chunk-types for the Count model

The model definition has two specifications for chunk-types used by this model:

```
(chunk-type count-order first second)
(chunk-type count-from start end count)
```

The **count-order** chunk-type specifies the slots that will be used to encode the ordering of numbers. The **count-from** chunk type specifies the slots that will be used for the **goal** buffer chunk of the model, and it has slots to hold the starting number, the ending number, and the current count.

1.5.2 Declarative Memory for the Count model

After the chunk-types we find the initial chunks placed into the declarative memory of the model using the **add-dm** command:

```
(add-dm
 (b ISA count-order first 1 second 2)
 (c ISA count-order first 2 second 3)
 (d ISA count-order first 3 second 4)
 (e ISA count-order first 4 second 5)
 (f ISA count-order first 5 second 6)
 (first-goal ISA count-from start 2 end 4))
```

Each of the lists in the add-dm command specifies one chunk. The first five define the counting facts named **b, c, d, e,** and **f**. They connect the number lower in the counting order (in slot **first**) to the number next in the counting order (in slot **second**). This is the knowledge that enables the model to count.

The last chunk created, **first-goal**, encodes the goal of counting from 2 (In slot **start**) to 4 (in slot **end**). Note that the chunk-type **count-from** has another slot called **count** which is not used when creating the chunk **first-goal**. Because the **count** slot is not included in the definition of the chunk **first-goal** that chunk does not have a slot named **count**.

1.5.3 Setting the Initial Goal

The next thing we see is a call to the command **goal-focus** with the chunk name first-goal:

```
(goal-focus first-goal)
```

The **goal-focus** command is provided by the goal module to allow the modeler to specify a chunk to place into the **goal** buffer when the model starts to run. Therefore, in this model the chunk named **first-goal** will be placed into the **goal** buffer when the model starts to run, and the results of that command can be seen in the first line of the trace shown above and copied here with color coding for reference:

```
0.000   GOAL     SET-BUFFER-CHUNK GOAL FIRST-GOAL NIL
```

It shows that at time 0.000 the goal module performed the set-buffer-chunk action (the ACT-R command for placing a chunk into a buffer) for the goal buffer with the chunk named **first-goal**. It also indicates that this action was not requested by a production (the "nil" at the end of the event details). That last part is not an important detail for this model, but we will describe places where that distinction may be important in later units.

1.5.4 The Productions

The rest of the model definition is the productions which can use the chunks from declarative memory to count, and we will look at each of the production specifications in detail along with the selection and firing of those productions as shown in the trace of the model run above.

1.5.4.1 The Start Production

```
(p start
   =goal>
      ISA          count-from
      start        =num1
      count        nil
 ==>
   =goal>
      ISA          count-from
      count        =num1
   +retrieval>
      ISA          count-order
      first        =num1
)
```

The LHS of the start production tests the **goal** buffer. It tests that there is a value in the start slot which it now references with the variable **=num1**. This is often referred to as binding the variable, as in, **=num1** is bound to the value that is in the start slot. It also tests the count slot for the value **nil**. The value **nil** is a special value that can be used when testing and setting slots. **Nil** is the Lisp symbol which represents both the boolean false and null (the empty list). Its use in a slot test is to check that the slot does not exist in the chunk. Thus, that is testing that the chunk in the **goal** buffer does not have a slot named count.

The RHS of the start production performs two actions. The first is a modification of the chunk in the **goal** buffer. That modification will add the slot named count to the chunk in the **goal** buffer (since the condition tested that it does not have such a slot) with the value bound to **=num1**. The

other action is a retrieval request. That request asks the declarative module to find a chunk that has the value which is bound to **=num1** in its **first** slot and place that chunk into the **retrieval** buffer.

Looking at the model trace, we see that the first production that gets selected and fired by the model is the production **start**:

```
0.000   PROCEDURAL           CONFLICT-RESOLUTION
0.000   PROCEDURAL           PRODUCTION-SELECTED START
0.000   PROCEDURAL           BUFFER-READ-ACTION GOAL
0.050   PROCEDURAL           PRODUCTION-FIRED START
```

The first line shows that the procedural module is performing an action called conflict-resolution. That action is the process which the procedural module uses to select which of the productions that matches the current state (if any) to fire next. The next line shows that among those that matched, the **start** production was selected. The important thing to remember is that the production was selected because its condition was satisfied. It did not get selected because it was the first production listed in the model or because it has the name start. The third line shows that the selected production's condition tested the chunk in the **goal** buffer. That last line, which happens 50 milliseconds later (time 0.050), shows that the **start** production has now fired and its actions will take effect. The 50ms time is a parameter of the procedural module, and by default every production will take 50ms between the time it is selected and when it fires.

The actions of the production are seen as the next two lines of the trace:

```
0.050   PROCEDURAL           MOD-BUFFER-CHUNK GOAL
0.050   PROCEDURAL           MODULE-REQUEST RETRIEVAL
```

Mod-buffer-chunk is the action which modifies a chunk in a buffer, in this case the **goal** buffer, and module-request indicates that a request is being sent to a module through the indicated buffer.

The next line of the trace is also a result of the RHS of the **start** production:

```
0.050   PROCEDURAL           CLEAR-BUFFER RETRIEVAL
```

That is the implicit clearing of the buffer which happens because of the request that was made.

The next line in the trace is a notification from the declarative module that it has received a request and has started the chunk retrieval process:

```
0.050   DECLARATIVE          start-retrieval
```

That is followed by the procedural system now trying to find a new production to fire:

```
0.050   PROCEDURAL           CONFLICT-RESOLUTION
```

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However, it is not followed by a notification of a production being selected, because there is no production whose condition is satisfied at this time.

The following two lines show the successful completion of the retrieval request by the declarative module and then the setting of the **retrieval** buffer with that chunk after another 50ms have passed.

```
0.100   DECLARATIVE              RETRIEVED-CHUNK C
0.100   DECLARATIVE              SET-BUFFER-CHUNK RETRIEVAL C
```

Now we see conflict resolution occurring again and this time the **increment** production is selected.

```
0.100   PROCEDURAL               CONFLICT-RESOLUTION
0.100   PROCEDURAL               PRODUCTION-SELECTED INCREMENT
```

1.5.4.2 The Increment Production

```
(P increment
  =goal>
     ISA           count-from
     count         =num1
   - end           =num1
  =retrieval>
     ISA           count-order
     first         =num1
     second        =num2
 ==>
  =goal>
     ISA           count-from
     count         =num2
  +retrieval>
     ISA           count-order
     first         =num2
  !output!         (=num1)
)
```

On the LHS of this production we see that it tests both the **goal** and **retrieval** buffers. In the test of the **goal** buffer it uses a modifier in the testing of the **end** slot:

```
  =goal>
     ISA           count-from
     count         =num1
   - end           =num1
```

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The "-" in front of the slot is the negative test modifier. It means that the following slot test must **not** be true for the test to be successful. The test is that the **end** slot of the chunk in the **goal** buffer have the value bound to the =**num1** variable (which is the value from the **count** slot of the chunk in the buffer). Thus, this test is true if the **end** slot of the chunk in the **goal** buffer does **not** have the same value as the **count** slot since they are tested with the same variable =**num1**. Note that the negation of the **end** slot test would also be true if the chunk in the **goal** buffer did not have a slot named **end** because a test for a slot value in a slot which does not exist is false, and thus the negation of that would be true.

The **retrieval** buffer test checks that there is a chunk in the **retrieval** buffer which has a value in its **first** slot that matches the current **count** slot from the **goal** buffer chunk and binds the variable =**num2** to the value of its **second** slot:

```
=retrieval>
    ISA         count-order
    first       =num1
    second      =num2
```

We can see that these two buffers were tested by the production in the next two lines of the trace:

```
 0.100   PROCEDURAL              BUFFER-READ-ACTION GOAL
 0.100   PROCEDURAL              BUFFER-READ-ACTION RETRIEVAL
```

Now we will look at the RHS of this production:

```
 =goal>
     ISA         count-from
     count       =num2
  +retrieval>
     ISA         count-order
     first       =num2
  !output!        (=num1)
```

The first two actions are very similar to those in the **start** production. It modifies the chunk in the **goal** buffer to change the value of the **count** slot to the next number, which is the value of the **second** slot of the chunk in the **retrieval** buffer, and it makes a retrieval request to get the chunk which indicates what number is next. The third action is a special command that can be used in the actions of a production:

```
    !output!        (=num1)
```

!output! (pronounced bang-output-bang) can be used on the RHS of a production to display information in the trace. It may be followed by a single item or a list of items, and the given item(s) will be printed in the trace when the production fires. In this production it is used to

display the numbers as the model counts. The results of the **!output!** in the first firing of **increment** can be seen in the next two lines of the trace:

```
     0.150   PROCEDURAL              PRODUCTION-FIRED INCREMENT
2
```

The output is displayed on one line in the trace after the notice that the production has fired. The items in the list to output can be variables as is the case here (=num1), constant items like (stopping), or a combination of the two e.g. (the number is =num). When a variable is included in the items to output the specific value to which it was bound in the production will be used in the output which is displayed. That is why the trace shows 2 instead of =num1.

The next few lines of the trace show the actions initiated by the **increment** production and they look very much like the actions that the **start** production generated. The **goal** buffer is modified, a retrieval request is made, a chunk is retrieved, and then that chunk is placed into the **retrieval** buffer:

```
     0.150   PROCEDURAL              MOD-BUFFER-CHUNK GOAL
     0.150   PROCEDURAL              MODULE-REQUEST RETRIEVAL
     0.150   PROCEDURAL              CLEAR-BUFFER RETRIEVAL
     0.150   DECLARATIVE             start-retrieval
     0.150   PROCEDURAL              CONFLICT-RESOLUTION
     0.200   DECLARATIVE             RETRIEVED-CHUNK D
     0.200   DECLARATIVE             SET-BUFFER-CHUNK RETRIEVAL D
```

We then see that the **increment** production is selected again:

```
     0.200   PROCEDURAL              CONFLICT-RESOLUTION
     0.200   PROCEDURAL              PRODUCTION-SELECTED INCREMENT
```

It will continue to be selected and fired until the value of the **count** and **end** slots of the goal chunk are the same, at which time its test of the **goal** buffer will fail. We see that it fires twice in the trace and then a different production is selected at .25 seconds into the run:

```
     0.250   PROCEDURAL              CONFLICT-RESOLUTION
     0.250   PROCEDURAL              PRODUCTION-SELECTED STOP
```

1.5.4.3 The Stop Production

```
(P stop
   =goal>
      ISA           count-from
      count         =num
      end           =num
==>
   -goal>
   !output!        (=num)
   )
```

The stop production matches when the values of the **count** and **end** slots of the chunk in the **goal** buffer are the same. The action it takes is to again print out the current number and to also clear the chunk from the **goal** buffer:

```
    0.300   PROCEDURAL              PRODUCTION-FIRED STOP
4
    0.300   PROCEDURAL              CLEAR-BUFFER GOAL
```

The final event that happens in the run is another attempt of conflict-resolution by the procedural module. No productions are found to match and no other events of any module are pending at this time (for instance a retrieval request being completed) so there is nothing more for the model to do and it stops running.

```
    0.300   PROCEDURAL              CONFLICT-RESOLUTION
    0.300   ------                  Stopped because no events left to process
```

1.6 Pattern Matching Exercise

To show you how ACT-R goes about matching a production, you will work through an exercise where you will manually fill in the bindings for the variables of the productions as they are selected. This is called instantiating the production. You need to do the following:

1. Load the count model if it is not currently loaded or reset it to its initial conditions if it has been loaded and already run. To reset the model you should press the "Reset" button on the Control Panel.

2. Press the "Stepper" button in the Control Panel to open the Stepper tool. This tool will pause the model before every operation it performs. For each event that shows as a line in the trace, the stepper will force the model to wait for your confirmation before handling that event. That provides you with the opportunity to inspect all of the components of the model as it progresses and can be a very valuable tool for debugging models. After each time a production is selected the Stepper will show the text of the production, the bindings for the variables as they matched that production, and a set of parameters for that production (which we will describe later in the tutorial). After the production is fired it will show the same information except that the production text will have the variables replaced with their bound values (referred to as being instantiated). After a retrieval request completes the Stepper will show the details of the chunk it retrieved and the corresponding parameters that lead to that chunk being the one retrieved (more on that in a later unit).

You are going to use a feature of this window that forces you to manually instantiate the productions before it will step past a production-selected event. That is, you will assign all of the variables the proper values when the production is selected. To enable this functionality of the Stepper, click the "Tutor Mode**"** checkbox at the top of the Stepper window.

3. Press the "Buffers" button in the Control Panel to bring up a new buffer inspection window. That will display a list of all the buffers for the existing modules. Selecting one from the list will display the chunk that is in that buffer in the text window to the right of the list. At this point all of the buffers are empty, but that will change as the model runs.

4. Now you should run the model by pressing the "Run" button in the Control Panel. The first action that occurs is the setting of the chunk in the **goal** buffer as was seen in the first line of the trace above:

```
0.000   GOAL    SET-BUFFER-CHUNK GOAL FIRST-GOAL NIL
```

That line should be displayed at the top of the Stepper window where it says "Next Step:" indicating the next action which will occur. Hitting the "Step" button in the Stepper window will allow that action to occur, and you will see that line printed out in the model trace and now shown as the "Last Stepped:" event in the Stepper window. You can now inspect the chunk in the **goal** buffer using the buffer inspection window which you opened previously. [Note, if you selected the **goal** buffer in that window before and it currently shows "buffer is empty" you will need to make that the active window (select it with the mouse or some other means) to have it update with the current information.]

1.6.1 The first-goal-0 Chunk and Buffer Chunk Copying

When you inspect the **goal** buffer you will see output that looks like this:

```
GOAL: FIRST-GOAL-0 [FIRST-GOAL]
FIRST-GOAL-0
   START  2
   END  4
```

The goal-focus command in the model made the goal module set the **goal** buffer to the chunk **first-goal**. The trace indicated that the chunk **first-goal** was used to set the buffer, but this output is displaying that a chunk named **first-goal-0** is currently in the **goal** buffer. Why is that? When a chunk is placed into a buffer the buffer always makes its own new copy of that chunk which is then placed into the buffer. The name of the chunk that was copied is shown in the buffer inspection window in square brackets after the name of the chunk actually in the buffer. The purpose for copying the chunk is to prevent the model from being able to alter the original chunk -- it cannot directly manipulate the information that it has learned previously, but it may use the contents of that knowledge to create new chunks.

The buffers can be thought of as note pads for manipulating and creating new chunks. Placing a chunk into a buffer corresponds to writing the contents of that chunk on the top page of the note pad. The information on the top page of the note pad can be manipulated by productions or any of the modules. Clearing the chunk from the buffer corresponds to tearing off the page with the current information and revealing a new empty page underneath. That torn off page containing the chunk is then filed away in the model's declarative memory and can no longer be changed.

1.6.2 Pattern Matching Exercise Continued

5. If you Step past the production-selected event you will come to the first production to match, **start**. It is shown in the bottom right pane of the Stepper window with all of the variables highlighted. Your task is to replace all of the variables with the values to which they are bound in the matching of this production. When you click on a highlighted variable in the production display of the stepper a new window will open in which you can enter the value for that variable. You must enter the value for every variable in the production (including multiple occurrences of the same variable) before it will allow you to progress to the next event.

Here is how you can determine the variable bindings:

- =**goal** will always bind to the name of the chunk in the **goal** buffer. This can be found with the Buffers viewer.

- =**retrieval** will always bind to the name of the chunk in the **retrieval** buffer. This can also be found with the Buffers viewer.

- To find the binding for other variables, you will use the Buffers viewer to look at the buffer which is being tested to find the value for the slot that is being tested with the variable.

- A variable will have the same value everywhere in a production that matches, and the bound values are displayed in the Stepper window as you enter them. Thus once you find the binding for a variable you can just refer to the Stepper to get the value for other occurrences of the variable in that production.

At any point in time, you can ask the tutor for help in binding a variable by hitting either the Hint or Help button of the entry dialog. A hint will instruct you on where to find the correct answer and help will just give you the correct answer.

6. Once the production is completely instantiated, you can continue stepping through the model run with the Step button. You should step the model to the next production that matches and watch how the contents of the **goal** and **retrieval** buffer change based on the actions taken by the **start** production.

7. To finish the run of the model you will need to instantiate two instances of the production i**ncrement** being selected and one instance of the **stop** production matching.

8. When you have completed this example and explored it as much as you want, go on to the next section of this unit, in which we will describe another example model.

1.7 The Addition Model

The second example model uses a slightly larger set of count facts to do a somewhat more complicated task. It will perform addition by counting up. Thus, given the goal to add 2 to 5 it

will count 5, 6, 7, and report the answer 7. You should now load the **addition** model, found in the "addition.lisp" file of unit 1, the same way you loaded the **count** model.

The initial count facts for the **addition** model are the same as those used for the **count** model with the inclusion of a fact that encodes 1 follows 0 and facts that encode counting from 7 up to 10. The chunk-type created for the goal information now has slots to hold the starting number (**arg1**), the number to be added (**arg2**), a slot for holding the current value counted to (**sum**), and a slot for holding the count that has been added so far (**count**):

```
(chunk-type add arg1 arg2 sum count)
```

Here is the initial chunk created for the **goal** buffer which indicates that it should add 2 to 5:

```
(second-goal ISA add arg1 5 arg2 2)
```

If you run this model (without having the Stepper open) you will see this trace:

```
0.000    GOAL                  SET-BUFFER-CHUNK GOAL SECOND-GOAL NIL
0.000    PROCEDURAL            CONFLICT-RESOLUTION
0.050    PROCEDURAL            PRODUCTION-FIRED INITIALIZE-ADDITION
0.050    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.050    DECLARATIVE           start-retrieval
0.050    PROCEDURAL            CONFLICT-RESOLUTION
0.100    DECLARATIVE           RETRIEVED-CHUNK F
0.100    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL F
0.100    PROCEDURAL            CONFLICT-RESOLUTION
0.150    PROCEDURAL            PRODUCTION-FIRED INCREMENT-SUM
0.150    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.150    DECLARATIVE           start-retrieval
0.150    PROCEDURAL            CONFLICT-RESOLUTION
0.200    DECLARATIVE           RETRIEVED-CHUNK A
0.200    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL A
0.200    PROCEDURAL            CONFLICT-RESOLUTION
0.250    PROCEDURAL            PRODUCTION-FIRED INCREMENT-COUNT
0.250    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.250    DECLARATIVE           start-retrieval
0.250    PROCEDURAL            CONFLICT-RESOLUTION
0.300    DECLARATIVE           RETRIEVED-CHUNK G
0.300    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL G
0.300    PROCEDURAL            CONFLICT-RESOLUTION
0.350    PROCEDURAL            PRODUCTION-FIRED INCREMENT-SUM
0.350    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.350    DECLARATIVE           start-retrieval
0.350    PROCEDURAL            CONFLICT-RESOLUTION
0.400    DECLARATIVE           RETRIEVED-CHUNK B
0.400    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL B
0.400    PROCEDURAL            CONFLICT-RESOLUTION
0.450    PROCEDURAL            PRODUCTION-FIRED INCREMENT-COUNT
0.450    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.450    DECLARATIVE           start-retrieval
0.450    PROCEDURAL            CONFLICT-RESOLUTION
0.500    DECLARATIVE           RETRIEVED-CHUNK H
0.500    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL H
0.500    PROCEDURAL            PRODUCTION-FIRED TERMINATE-ADDITION
```

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```
   0.500   PROCEDURAL            CONFLICT-RESOLUTION
   0.500   ------                Stopped because no events left to process
```

The first thing you may notice is that there is less information in the trace of this model than there was in the trace of the **count** model. This model is set to show the default trace detail level which should make it easier to read the sequence of productions that fire.

In this sequence we see that the model alternates between incrementing the count from 0 to 2 and incrementing the sum from 5 to 7. The production **initialize–addition** starts things going and makes a retrieval request for the chunk which indicates the number following the arg1 number. **Increment-sum** then uses that retrieved chunk to update the current sum and requests a retrieval of a chunk to determine the next count value. That production fires alternately with **increment-count**, which processes the retrieval of the counter increment and requests a retrieval of an increment to the sum.　**Terminate-addition** recognizes when the counter equals the second argument of the addition and it modifies the **goal** to make the model output the answer and stop.

1.7.1 The initialize-addition and terminate-addition productions

The production **initialize-addition** initializes an addition process whereby the model tries to count up from the first digit a number of times that equals the second digit and the production **terminate-addition** recognizes when this has been completed.

```
(P initialize-addition
   =goal>
      ISA          add
      arg1         =num1
      arg2         =num2
      sum          nil
  ==>
   =goal>
      ISA          add
      sum          =num1
      count        0
   +retrieval>
      ISA          count-order
      first        =num1
)
```

When the chunk in the **goal** buffer has values for the **arg1** and **arg2** slots but does not have a **sum** slot the **initialize-addition** production matches. Its action modifies the **goal** buffer chunk to add a **sum** slot set to be the first digit and a **count** slot to be 0, and it makes a retrieval request for a chunk to find the number that follows =**num1**.

Pairs of productions will apply after this to keep incrementing the **sum** and the **count** slots until the **count** slot equals the **arg2** slot, at which time **terminate-addition** matches:

```
(P terminate-addition
   =goal>
      ISA          add
      count        =num
      arg2         =num
      sum          =answer
  ==>
   =goal>
      ISA          add
      count        nil
   !output!        =answer
)
```

This production removes the **count** slot from the **goal** buffer chunk by setting it to the symbol **nil**. Previously we saw the special symbol **nil** used to test that a slot does not exist in a chunk, and here we see the reciprocal modification for removing a slot. This causes the model to stop because other than **initialize-addition**, (which requires that the sum slot not exist) all of the other productions require the goal to have a **count** slot. So, after this production fires none of the productions will match the chunk in the **goal** buffer.

1.7.2 The increment-sum and increment-count productions

The two productions that apply repeatedly between the previous two are **increment-sum**, which uses the retrieval of the sum increment and requests a retrieval of the count increment, and **increment-count**, which uses the retrieval of the count increment and requests a retrieval of the sum increment.

```
(P increment-sum
   =goal>
      ISA          add
      sum          =sum
      count        =count
    - arg2         =count
   =retrieval>
      ISA          count-order
      first        =sum
      second       =newsum
  ==>
   =goal>
      ISA          add
      sum          =newsum
   +retrieval>
      ISA          count-order
      first        =count
)
```

```
(P increment-count
   =goal>
      ISA          add
      sum          =sum
      count        =count
   =retrieval>
      ISA          count-order
      first        =count
      second       =newcount
  ==>
   =goal>
      ISA          add
      count        =newcount
   +retrieval>
      ISA          count-order
      first        =sum
)
```

Some terminology which is often used when discussing productions which use a chunk that was placed into a buffer and then immediately clear that chunk from the buffer is to say that it "harvests" the chunk. Both of these productions harvest the chunk from the **retrieval** buffer which resulted from the request of the other because the retrieval request action automatically clears the buffer. We would not say that they harvest the **goal** chunk because it is modified and remains in the buffer.

1.7.3 The Addition Exercise

Now, as you did with the **count** model, you should use the tutor mode of the Stepper to step through the matching of the four productions for the **addition** model. Once you have completed that you should move on to the next model.

1.8 The Semantic Model

The last example model for this unit is the **semantic** model, found in the "semantic.lisp" file of tutorial unit 1. You should load that model file now. When you do so, you may notice that there is some text displayed in the window that indicates it loaded successfully and that text is also displayed in the ACT-R window. For now, you can ignore that output and just press "Ok" as you have for the previous models. We will come back to that after describing the operation of the model.

This model contains chunks which encode the following network of categories and properties.
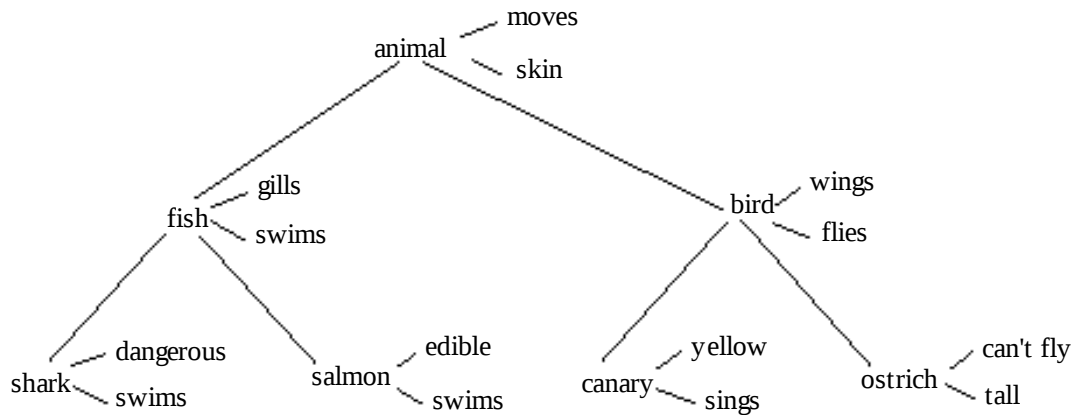
The productions it has are capable of searching this network to make decisions about whether one category is a member of another category.

1.8.1 Encoding of the Semantic Network

All of the links in this network are encoded by chunks with the slots **object**, **attribute**, and **value**. For instance, the following three chunks encode the links involving shark:

```
(p1 ISA property object shark attribute dangerous value true)
(p2 ISA property object shark attribute locomotion value swimming)
(p3 ISA property object shark attribute category value fish)
```

p1 encodes that a shark is dangerous by encoding the value as **true** for an attribute with the value **dangerous**. **p2** encodes that a shark can swim by encoding the value **swimming** with the attribute of **locomotion**. **p3** encodes that a shark is a fish by encoding **fish** as the value and the attribute as **category**.

There are of course many other ways one could encode this information, for example instead of using slots named attribute and value it seems like one could just use the slot as the attribute and the value as its value for example:

```
(p1 object shark dangerous true)
(p2 object shark locomotion swimming)
(p3 object shark category fish)
```

or perhaps even collapsing all of that information into a single chunk describing a shark:

```
(shark dangerous true locomotion swimming category fish)
```

How one chooses to organize the knowledge in a model can have an effect on the results, and that can be a very important aspect of the modeling task. For example, choosing to encode the

properties in separate chunks vs a single chunk will affect how that information is reinforced (all the items together vs each individually) as well as how it may be affected by the spreading of activation for related information (both topics which will be discussed in later units). Typically, there is no one "right way" to write a model and one should make the choices necessary based on the objectives of the modeling effort and any related research which provides guidance.

For this model we have chosen the representation for practical reasons – it provides a useful example. It might seem that the second representation would still be better for that, and such a representation could have been used for the category searching model described below since we are only searching for the category attribute which could have been encoded directly into the productions. However, it would be difficult to use that representation with what has been discussed so far in the tutorial, to perform a more general search for information in the network. When we get to unit 8 of the tutorial we will see some more advanced aspects of the pattern matching allowed in productions which could be used with such a representation to make the searching more general.

1.8.2 Testing for Category Membership

This model performs a test for category membership when a chunk in the **goal** buffer has object and category slot values and no slot named judgment. There are 3 different starting goals provided in the initial chunks for the model. The one initially placed in the **goal** buffer is **g1**:

```
(g1 ISA is-member object canary category bird)
```

which represents a test to determine if a canary is a bird. That chunk does not have a judgment slot, and the model will add that slot to indicate a result of yes or no. If you run the model with **g1** in the **goal** buffer (which is placed there by the call to goal-focus in the model definition) you will see the following trace:

```
0.000   GOAL                SET-BUFFER-CHUNK GOAL G1 NIL
0.000   PROCEDURAL          CONFLICT-RESOLUTION
0.050   PROCEDURAL          PRODUCTION-FIRED INITIAL-RETRIEVE
0.050   PROCEDURAL          CLEAR-BUFFER RETRIEVAL
0.050   DECLARATIVE         start-retrieval
0.050   PROCEDURAL          CONFLICT-RESOLUTION
0.100   DECLARATIVE         RETRIEVED-CHUNK P14
0.100   DECLARATIVE         SET-BUFFER-CHUNK RETRIEVAL P14
0.100   PROCEDURAL          CONFLICT-RESOLUTION
0.150   PROCEDURAL          PRODUCTION-FIRED DIRECT-VERIFY
0.150   PROCEDURAL          CLEAR-BUFFER RETRIEVAL
0.150   PROCEDURAL          CONFLICT-RESOLUTION
0.150   ------              Stopped because no events left to process
```

If you inspect the goal chunk after the model stops it will look like this:

```
GOAL: G1-0
G1-0
   OBJECT   CANARY
   CATEGORY  BIRD
   JUDGMENT  YES
```

This is among the simplest cases possible for this network of facts and only requires the retrieval of this property to determine the answer:

```
(p14 ISA property object canary attribute category value bird)
```

There are two productions involved. The first, **initial-retrieve**, requests the retrieval of categorical information and the second, **direct-verify,** harvests that information and sets the **judgment** slot to **yes**:

```
(p initial-retrieve
   =goal>
      ISA           is-member
      object        =obj
      category      =cat
      judgment      nil
==>
   =goal>
      judgment      pending
   +retrieval>
      ISA           property
      object        =obj
      attribute     category
)
```

Initial-retrieve tests that there are object and category slots in the **goal** buffer's chunk and that it does not have a judgment slot. Its action is to modify the chunk in the **goal** buffer by adding a judgment slot with the value pending and to request the retrieval of a chunk from declarative memory which indicates a category for the current object.

After that production fires and the chunk named p14 is retrieved the **direct-verify** production matches and fires:

```
(P direct-verify
   =goal>
      ISA           is-member
      object        =obj
      category      =cat
      judgment      pending
   =retrieval>
      ISA           property
      object        =obj
      attribute     category
```

```
      value         =cat
==>
   =goal>
      judgment    yes
)
```

That production tests that the chunk in the **goal** buffer has values in the object and category slots and a judgment slot with the value pending, and that the **retrieval** buffer has an object slot with the same value as the object slot of the chunk in the **goal** buffer, an attribute slot with the value category, and a value slot with the same value as the category slot of the chunk in the **goal** buffer. Its action is to modify the chunk in the **goal** buffer by setting the judgment slot to the value yes.

You should now work through the pattern matching process in the tutor mode of the Stepper with the goal set to **g1**.

1.8.3 Chaining Through Category Links

A slightly more complex case occurs when the category is not an immediate super ordinate of the indicated object and it is necessary to chain through an intermediate category. An example where this is necessary is in the verification of whether a canary is an animal, and such a test is created in chunk **g2**:

```
(g2 ISA is-member object canary category animal)
```

You should change the goal-focus call in the model file to set the goal to **g2** instead of **g1**. After you save that change to the file you must load the model again. That can be done using the "Reload" button on the Control Panel which will load the last model file that was loaded, or you can use the "Load ACT-R code" button to select the file and load it. [Note: it is also possible to update the **goal** buffer chunk without editing the model file and loading it again, and the unit1_code text shows how that could be done.]

Running the model with chunk **g2** as the goal will result in the following trace:

```
0.000    GOAL                  SET-BUFFER-CHUNK GOAL G2 NIL
0.000    PROCEDURAL            CONFLICT-RESOLUTION
0.050    PROCEDURAL            PRODUCTION-FIRED INITIAL-RETRIEVE
0.050    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.050    DECLARATIVE           start-retrieval
0.050    PROCEDURAL            CONFLICT-RESOLUTION
0.100    DECLARATIVE           RETRIEVED-CHUNK P14
0.100    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL P14
0.100    PROCEDURAL            CONFLICT-RESOLUTION
0.150    PROCEDURAL            PRODUCTION-FIRED CHAIN-CATEGORY
0.150    PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.150    DECLARATIVE           start-retrieval
0.150    PROCEDURAL            CONFLICT-RESOLUTION
0.200    DECLARATIVE           RETRIEVED-CHUNK P20
0.200    DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL P20
0.200    PROCEDURAL            CONFLICT-RESOLUTION
```

```
     0.250   PROCEDURAL              PRODUCTION-FIRED DIRECT-VERIFY
     0.250   PROCEDURAL              CLEAR-BUFFER RETRIEVAL
     0.250   PROCEDURAL              CONFLICT-RESOLUTION
     0.250   ------                  Stopped because no events left to process
```

This trace is similar to the previous one except that it involves an extra production, **chain-category**, which retrieves the category in the case that an attribute has been retrieved which does not immediately allow a decision to be made.

```
(P chain-category
   =goal>
      ISA           is-member
      object        =obj1
      category      =cat
      judgment      pending
   =retrieval>
      ISA           property
      object        =obj1
      attribute     category
      value         =obj2
    - value         =cat
==>
   =goal>
      object        =obj2
   +retrieval>
      ISA           property
      object        =obj2
      attribute     category
)
```

This production tests that the chunk in the **goal** buffer has values in the object and category slots and a judgment slot with the value of pending, and that the chunk in the **retrieval** buffer has an object slot with the same value as the object slot of the chunk in the **goal** buffer, an attribute slot with the value category, a value in the value slot, and that the value in the value slot is not the same as the value of the category slot of the chunk in the **goal** buffer. Its action is to modify the chunk in the **goal** buffer by setting the object slot to the value from the value slot of the chunk in the **retrieval** buffer and to request the retrieval of a chunk from declarative memory which has that same value in its object slot and the value category in its attribute slot.

You should now go through the pattern matching exercise in the tutor mode of the Stepper with **g2** set as the goal.

1.8.4 The Failure Case

Now change the initial goal to the chunk **g3** and reload the model file.

```
(g3 ISA is-member object canary category fish)
```

If you run the model with this goal, you will see what happens when the chain reaches a dead end:

```
0.000    GOAL                   SET-BUFFER-CHUNK GOAL G3 NIL
0.000    PROCEDURAL             CONFLICT-RESOLUTION
0.050    PROCEDURAL             PRODUCTION-FIRED INITIAL-RETRIEVE
0.050    PROCEDURAL             CLEAR-BUFFER RETRIEVAL
0.050    DECLARATIVE            start-retrieval
0.050    PROCEDURAL             CONFLICT-RESOLUTION
0.100    DECLARATIVE            RETRIEVED-CHUNK P14
0.100    DECLARATIVE            SET-BUFFER-CHUNK RETRIEVAL P14
0.100    PROCEDURAL             CONFLICT-RESOLUTION
0.150    PROCEDURAL             PRODUCTION-FIRED CHAIN-CATEGORY
0.150    PROCEDURAL             CLEAR-BUFFER RETRIEVAL
0.150    DECLARATIVE            start-retrieval
0.150    PROCEDURAL             CONFLICT-RESOLUTION
0.200    DECLARATIVE            RETRIEVED-CHUNK P20
0.200    DECLARATIVE            SET-BUFFER-CHUNK RETRIEVAL P20
0.200    PROCEDURAL             CONFLICT-RESOLUTION
0.250    PROCEDURAL             PRODUCTION-FIRED CHAIN-CATEGORY
0.250    PROCEDURAL             CLEAR-BUFFER RETRIEVAL
0.250    DECLARATIVE            start-retrieval
0.250    PROCEDURAL             CONFLICT-RESOLUTION
0.300    DECLARATIVE            RETRIEVAL-FAILURE
0.300    PROCEDURAL             CONFLICT-RESOLUTION
0.350    PROCEDURAL             PRODUCTION-FIRED FAIL
0.350    PROCEDURAL             CLEAR-BUFFER RETRIEVAL
0.350    PROCEDURAL             CONFLICT-RESOLUTION
0.350    ------                 Stopped because no events left to process
```

Here we see the declarative memory module reporting that a retrieval-failure occurred at time 0.3 which is then followed by the production **fail** firing. The **fail** production uses a test on the LHS that we have not yet seen.

1.8.5 A Query in the Condition

In addition to testing the chunks in the buffers as has been done in all of the productions we have seen to this point, it is also possible to query the status of the buffer itself and the module which controls it. This is done using a "**?**" instead of an "=" before the name of the buffer. There is a fixed set of queries which can be made of the buffer itself. The buffer's module must respond to some specific queries, but may have any number of additional queries for its specific operations to which it will respond. The result of a query will be either true or false. If any query tested in a production has a result which is false, then the production does not match.

1.8.5.1 Querying the buffer itself

When querying the buffer itself, it can be in one of three mutually exclusive situations: there can be a chunk in the buffer, a failure can be indicated, or the buffer can be empty with no failure noted. If there is a chunk in the buffer or a failure has been indicated, then it is also possible to test whether that was the result of a requested action or not. Here are examples of the possible queries which can be made to test the status of a buffer, using the **retrieval** buffer for the examples.

This query will be true if there is a chunk in the **retrieval** buffer and false if there is not:

```
?retrieval>
    buffer        full
```

This query will be true if a failure has been noted for the **retrieval** buffer and false if not:

```
?retrieval>
    buffer        failure
```

This query will be true if there is not a chunk in the **retrieval** buffer and there is not a failure indicated and false if there is either a chunk in the buffer or a failure has been indicated:

```
?retrieval>
    buffer        empty
```

This query will be true if there is either a chunk in the **retrieval** buffer or the failure condition has occurred for the **retrieval** buffer, and that chunk or failure was the result of a request made to the buffer's module. Otherwise, it will be false:

```
?retrieval>
    buffer        requested
```

This query will be true if there is either a chunk in the **retrieval** buffer or the failure condition has occurred for the **retrieval** buffer, and that chunk or failure happened without a request being made to the buffer's module (later units will describe modules which can act without being requested to do so). Otherwise, it will be false:

```
?retrieval>
    buffer        unrequested
```

1.8.5.2 Querying a buffer's module

The queries that are available for every module allow one to test for one of three possible states of the module: free, busy, or error. Below are examples of those queries again using the **retrieval** buffer.

This query will be true if the **retrieval** buffer's module (the declarative module) is not currently performing an action and will be false if it is currently performing an action:

```
?retrieval>
    state         free
```

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This query will be true if the **retrieval** buffer's module is currently performing an action and will be false if it is not currently performing an action:

```
?retrieval>
    state        busy
```

This query will be true if an error has occurred in the declarative module since the last request made to the **retrieval** buffer and false if there has been no error:

```
?retrieval>
    state        error
```

The module's state error query is related to the buffer failure query because when the module encounters an error it will note that as a failure in the buffer, but they may not always both be true. That is because the buffer's failure state is cleared whenever the buffer is cleared, either explicitly with a buffer clear action or implicitly when a request is made to the buffer. However, the module's error state will remain set until the module clears it, and the conditions for clearing the module's error will vary depending on the operation of the particular module. Testing the buffer failure is usually a better choice because of the consistency of its operation across buffers and will be used for the models in the tutorial, but in some circumstances one may find it useful to query a module's internal error state instead.

Unlike the buffer conditions of empty, full, and failure, a module's states of free, busy, and error are not mutually exclusive e.g. a module can be both free and indicate that an error occurred.

Modules can also provide other queries that are specific to their operation. The declarative module for example provides a query called recently-retrieved which can be tested to determine if the chunk that was retrieved had also been retrieved previously:

```
?retrieval>
    recently-retrieved  t
```

1.8.5.3 Using queries in productions

When specifying queries in a production multiple queries can be made of a single buffer. This query would check if the **retrieval** buffer were currently empty and that the declarative module was not currently handling a request:

```
?retrieval>
    buffer       empty
    state        free
```

One can also use the optional negation modifier "-" before a query to test that such a condition is not true. Thus, either of these tests would be true if the declarative module was not currently handling a request:

```
    ?retrieval>
       state        free
```

or

```
    ?retrieval>
      - state        busy
```

1.8.6 The fail production

Here is the production that fires in response to a category request not being found.

```
(P fail
   =goal>
       ISA         is-member
       object      =obj1
       category    =cat
       judgment    pending

   ?retrieval>
       buffer      failure
==>
   =goal>
       judgment    no
)
```

Note the query for a **retrieval** buffer failure in the condition of this production. When a retrieval request does not succeed, in this case because there is no chunk in declarative memory which matches the specification requested, the buffer will indicate that as a failure. In this model, this will happen when one gets to the top of a category hierarchy and there are no super ordinate categories.

You should now make sure your goal is set to **g3**, and then go through the pattern matching exercise using the tutor mode of the Stepper tool one final time.

1.8.7 Model Warnings

Now that you have worked through the examples we will examine another detail which you might have noticed while working on this model. When you load or reload the **semantic** model there are the following warnings displayed in the Successful load window and the ACT-R window:

```
#|Warning: Creating chunk CATEGORY with no slots |#
#|Warning: Creating chunk PENDING with no slots |#
#|Warning: Creating chunk YES with no slots |#
#|Warning: Creating chunk NO with no slots |#
```

Output that begin with "#|Warning:" indicates warnings from ACT-R. These indicate that there is something in the model that may need to be addressed. This differs from warnings or errors which may be reported by the Lisp which implements the ACT-R system that can occur because of problems in the syntax or structure of the Lisp code in the model file. If you see ACT-R warnings when loading a model you should always read through them to make sure that there is not a serious problem in the model.

In this case, the warnings are telling you that the model uses chunks named **category, pending, yes,** and **no,** but does not explicitly define them and thus they are being created automatically. That is fine in this case. Those chunks are being used as explicit markers in the productions and there are no problems caused by allowing the system to create them automatically because they are arbitrary names that were used when writing the productions.

If there had been a typo in one of the productions however, for instance misspelling pending in one of them as "pneding", the warnings may have shown something like this:

```
#|Warning: Creating chunk PNEDING with no slots |#
```

That would provide you with an opportunity to notice the discrepancy and fix the problem before running the model and then trying to determine why it did not perform as expected.

There are many other ACT-R warnings that may be displayed and you should always read the warnings which occur when loading a model to make sure that there are no serious problems before you start running the model. Most warnings which are not a serious problem can be eliminated with some additional declarations or changes to the model. For example, if we wanted to eliminate these warnings we could explicitly create those chunks in the model. With what we have seen so far that would be done by adding them to declarative memory with the other chunks that are created, but later in the tutorial we will show a better approach that does not require adding them to the model's memory.

1.9 Building a Model

We would like you to now construct the pieces of an ACT-R model on your own. The "tutor-model.lisp" file included with unit 1 contains the basic code necessary for a model, but does not have any of the declarative or procedural elements defined. The instructions that follow will guide you through the creation of those components. You will be constructing a model that can perform the addition of two two-digit numbers using this process to add the numbers (which is of course not the only way one could describe this task):

To add two two-digit numbers start by adding the ones digits of the two numbers. After adding the ones digits of the numbers determine if there is a carry by checking if that result is equal to 10 plus some number. If it is, then that number is the answer for the ones column and there is a carry of 1 for the tens column. If it is not, then that result is the answer for the ones column and there is no carry. Then add the digits in the tens column. If there is no carry from the ones column then that sum is the answer for the tens column and the task is done. If there is a carry from the ones column then add the carry to that sum and make that the answer for the tens column to finish the task.

Once all of the pieces have been created as described below to implement that process, you should be able to load and run the model to produce a trace that looks like this:

```
0.000   GOAL                  SET-BUFFER-CHUNK GOAL GOAL NIL
0.000   PROCEDURAL            CONFLICT-RESOLUTION
0.050   PROCEDURAL            PRODUCTION-FIRED START-PAIR
0.050   PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.050   DECLARATIVE           start-retrieval
0.050   PROCEDURAL            CONFLICT-RESOLUTION
0.100   DECLARATIVE           RETRIEVED-CHUNK FACT67
0.100   DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL FACT67
0.100   PROCEDURAL            CONFLICT-RESOLUTION
0.150   PROCEDURAL            PRODUCTION-FIRED ADD-ONES
0.150   PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.150   DECLARATIVE           start-retrieval
0.150   PROCEDURAL            CONFLICT-RESOLUTION
0.200   DECLARATIVE           RETRIEVED-CHUNK FACT103
0.200   DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL FACT103
0.200   PROCEDURAL            CONFLICT-RESOLUTION
0.250   PROCEDURAL            PRODUCTION-FIRED PROCESS-CARRY
0.250   PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.250   DECLARATIVE           start-retrieval
0.250   PROCEDURAL            CONFLICT-RESOLUTION
0.300   DECLARATIVE           RETRIEVED-CHUNK FACT34
0.300   DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL FACT34
0.300   PROCEDURAL            CONFLICT-RESOLUTION
0.350   PROCEDURAL            PRODUCTION-FIRED ADD-TENS-CARRY
0.350   PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.350   DECLARATIVE           start-retrieval
0.350   PROCEDURAL            CONFLICT-RESOLUTION
0.400   DECLARATIVE           RETRIEVED-CHUNK FACT17
0.400   DECLARATIVE           SET-BUFFER-CHUNK RETRIEVAL FACT17
0.400   PROCEDURAL            CONFLICT-RESOLUTION
0.450   PROCEDURAL            PRODUCTION-FIRED ADD-TENS-DONE
0.450   PROCEDURAL            CLEAR-BUFFER RETRIEVAL
0.450   PROCEDURAL            CONFLICT-RESOLUTION
0.450   ------                Stopped because no events left to process
```

There is a working solution model included with the unit 1 files, and it is also described in the code description text for this unit. Thus, if you have problems you can consult that for help, but you should try to complete these tasks without looking first.

You should now open the tutor-model.lisp file in a text editor if you have not already. The following sections will describe the components that you should add to the file in the places indicated by comments in the model (the lines that begin with the semicolons) to construct a model for performing this task. There are of course many ways one could represent the addition

facts and process them using productions to perform the addition, but the description below corresponds to the solution model which is provided for reference and thus should be followed explicitly if you want to be able to compare to that as you go along.

1.9.1 Chunk-types

The first thing we should do is define the chunk-types that we will use in writing the model. There are two chunk-types which we will define for doing this task. One to represent addition facts and one to represent the goal chunk which holds the components of the task for the model and the correct answer when it is done. These chunk types will be created with the **chunk-type** command as described in section 1.4.2.

1.9.1.1 Addition Facts

The first chunk-type you should create is one to represent the addition facts. It should be named **addition-fact** and have slots named **addend1**, **addend2,** and **sum**. Chunks with these slots will represent the basic addition facts for addends from 0-10.

1.9.1.2 The Goal Chunk Type

The other chunk type you should create is one to represent the goal of adding two two-digit numbers. It should be named **add-pair.** It will have slots to encode all of the necessary components of the task. It should have two slots to represent the ones digit and the tens digit of the first number called **one1** and **ten1** respectively. It will have two more slots to hold the ones digit and the tens digit of the second number called **one2** and **ten2,** and two slots to hold the answer, called **one-ans** and **ten-ans.** It will also need a slot to hold any information necessary to process a carry from the addition in the ones column to the tens column which should be called **carry**.

1.9.2 Chunks

We are now going to define the chunks that will allow the model to solve the problem 36 + 47 and place them into the model's declarative memory. This is done using the **add-dm** command which was described in section 1.4.3.

1.9.2.1 The Addition Facts

You need to create addition facts which encode the following math facts in the model's declarative memory to be able to solve this problem with the productions which will be described later:

```
3+4=7
6+7=13
10+3=13
1+7=8
```

They will use the slots of the type addition-fact and should be named based on their addends. For example, the fact that 3+4=7 should be named **fact34**. The addends and sums for these facts will be the corresponding numbers. Thus, **fact34** will have slots with the values 3, 4, and 7.

1.9.2.2 The Initial Goal

You should now create a chunk named **goal** which encodes that the goal is to add 36+47 which will use slots from the add-pair chunk-type. This should be done by specifying the values for the ones and tens digits of the two numbers and leaving all of the other slots empty.

1.9.2.3 Checking the results so far

Once you have completed adding the chunk-types and chunks to the model you should be able to save the file and then load it to inspect the components you have created. To see the chunks you have created you can press the "Declarative" button on the Control Panel. That will open a declarative memory viewer which allows you to see all of the chunks in the model's declarative memory (every time you press that button a new declarative viewer window will be opened so that you can view different chunks at the same time when needed). To view a particular chunk with that tool select it in the list of chunks on the left of the window. The window on the right will then show the declarative parameters for that chunk (which will be described in later units) along with the slots and values for that chunk.

Once you are satisfied with the chunks that you have created you can move on to creating the productions which will use those chunks.

1.9.3 Productions

So far, we have been looking mainly at the individual productions in the models. However, a model really only functions because of the interaction of the productions it contains. Essentially, the action of one production will set the state so that the condition for another production can match, which has an action that sets the state to allow another to match, and so on. It is that sequence of productions firing, each of which performs some small step, which leads to performing the entire task, and one of the challenges of cognitive modeling is determining how to perform those small steps in a way that is both capable of performing the task and consistent with human performance on that task – just "doing the task" is not usually the objective for creating a model with a cognitive architecture like ACT-R.

Your task now is to write the ACT-R productions which perform the steps described in English above to do multi-column addition. To do that you will need to use the ACT-R **p** command to specify the productions as described in section 1.4.4, and to help with that we will further detail six productions which will implement that process using the chunk-types and chunks created previously.

START-PAIR

If the goal buffer contains slots holding the ones digits of two numbers and does not have a slot for holding the ones digit of the answer then modify the goal to add the slot one-ans and set it to

a value of **busy** and make a retrieval request for the chunk indicating the sum of those ones digits.

ADD-ONES

If the chunk in the goal buffer indicates that it is **busy** waiting for the answer for the addition of the ones digits and a chunk has been retrieved containing the sum of the ones digits then modify the goal chunk to set the one-ans slot to that sum and add a slot named carry with a value **busy**, and make a retrieval request for an addition fact to determine if that sum is equal to 10 plus some number.

PROCESS-CARRY

If the chunk in the goal buffer indicates that it is **busy** processing a carry, a chunk has been retrieved which indicates that 10 plus a number equals the value in the one-ans slot, and the digits for the tens column of the two numbers are available in the goal chunk then set the carry slot of the goal to 1, set the one-ans slot of the goal to the other addend from the chunk in the retrieval buffer, set the ten-ans slot to the value **busy**, and make a retrieval request for an addition fact of the sum of the tens column digits.

NO-CARRY

If the chunk in the goal buffer indicates that it is **busy** processing a carry, a failure to retrieve a chunk occurred, and the digits for the tens column of the two numbers are available in the goal chunk then remove the carry slot from the goal by setting it to **nil**, set the ten-ans slot to the value **busy**, and make a retrieval request for an addition fact of the sum of the tens column digits.

ADD-TENS-DONE

If the chunk in the goal buffer indicates that it is **busy** computing the sum of the tens digits, there is no carry slot in the goal chunk, and there is a chunk in the retrieval buffer with a value in the sum slot then set the ten-ans slot of the chunk in the goal buffer to that sum.

ADD-TENS-CARRY

If the chunk in the goal buffer indicates that it is **busy** computing the sum of the tens digits, the carry slot of the goal chunk has the value 1, and there is a chunk in the retrieval buffer with a value in the sum slot then remove the carry slot from the chunk in the goal buffer, and make a retrieval request for the addition of 1 plus the current sum from the retrieval buffer.

1.9.4 Running the model

When you are finished entering the productions, save your model, reload it, and then run it.

If your model is correct, then it should produce a trace that looks like the one shown above, and the correct answer should be encoded in the **ten-ans** and **one-ans** slots of the chunk in the **goal** buffer:

```
GOAL-0
   ONE1   6
   TEN1   3
   ONE2   7
   TEN2   4
   TEN-ANS   8
   ONE-ANS   3
```

1.9.5 Incremental Creation of Productions

It is also possible to write just one or two productions and test them out first before you go on to try to write the rest – to make sure that you are on the right track. For instance, this is the trace you would get after successfully writing the first two productions and then running the model:

```
0.000   GOAL               SET-BUFFER-CHUNK GOAL GOAL NIL
0.000   PROCEDURAL         CONFLICT-RESOLUTION
0.050   PROCEDURAL         PRODUCTION-FIRED START-PAIR
0.050   PROCEDURAL         CLEAR-BUFFER RETRIEVAL
0.050   DECLARATIVE        start-retrieval
0.050   PROCEDURAL         CONFLICT-RESOLUTION
0.100   DECLARATIVE        RETRIEVED-CHUNK FACT67
0.100   DECLARATIVE        SET-BUFFER-CHUNK RETRIEVAL FACT67
0.100   PROCEDURAL         CONFLICT-RESOLUTION
0.150   PROCEDURAL         PRODUCTION-FIRED ADD-ONES
0.150   PROCEDURAL         CLEAR-BUFFER RETRIEVAL
0.150   DECLARATIVE        start-retrieval
0.150   PROCEDURAL         CONFLICT-RESOLUTION
0.200   DECLARATIVE        RETRIEVED-CHUNK FACT103
0.200   DECLARATIVE        SET-BUFFER-CHUNK RETRIEVAL FACT103
0.200   PROCEDURAL         CONFLICT-RESOLUTION
0.200   ------             Stopped because no events left to process
```

The first production, **start-pair**, has fired and successfully requested the retrieval of the addition fact **fact67**. The next production, **add-ones**, then fires and makes a retrieval request to determine if there is a carry. That chunk is retrieved and then because there are no more productions the system stops. You may find it helpful to try out the productions occasionally as you write them to make sure that the model is working as you progress instead of writing all the productions and then trying to debug them all at once.

1.9.6 Debugging the Productions

In the event that your model does not run correctly you will need to determine why that is so you can fix it. One tool that can help with that is the "Why not?" button in the Procedural viewer. To use that, first press the "Procedural" button on the Control Panel to open a viewer for the productions in the model. That tool is very similar to the Declarative viewer described previously – there is a list of productions on the left and selecting one will show the parameters and text of the production on the right. Pressing the "Why not?" button at the top of the Procedural viewer window when there is a production selected in the list will open another window. If the chosen production matches the current state of the buffers then the new window will indicate that it matches and display the instantiation of that production. If the chosen

production does not match the current state then the text of the production will be printed and an indication of the first mismatching item from the LHS of the production will be indicated, for example, when the start-pair production described above does not match it might say "The chunk in the GOAL buffer has the slot ONE-ANS" since that production specifies that the **goal** buffer should not have a slot named one-ans.

The Stepper is also an important tool for use when debugging a model because while the model is stopped you can inspect everything in the model using all of the other tools. For more information on writing and debugging ACT-R models you should also read the "Modeling" text which accompanies this unit. That file is the "unit1_modeling" document, and each of the odd numbered units in the tutorial will include a modeling text with details on potential issues one may encounter and ways to debug those issues.