

## 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, but it is not a complete reference on the theory of ACT-R. More detailed information on the theory can be found in the paper “An integrated theory of the mind”, which is available on the ACT-R website at: <http://act-r.psy.cmu.edu/publications/pubinfo.php?id=526>, and also in the book “How Can the Human Mind Occur in the Physical Universe?”.

The goals of this unit are to introduce the knowledge representations which are used in ACT-R, present the formal notation for specifying that knowledge within an ACT-R model, and to describe how those types of knowledge interact in an ACT-R model.

### 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**. Thus 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 defined by its **chunk-type** and its **slots**. One can think of **chunk-types** as categories (e.g., birds) and slots as category attributes (e.g., color or size). 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 type of the first chunk is **chase** and its slots are **agent** and **object**. The **isa** slot is special and specifies the type of the chunk. The type of the second chunk is **addition-fact** and its slots are **addend1**, **addend2**, and **sum**.

```
Action023
  isa chase
  agent dog
  object cat
```

```
Fact3+4
  isa addition-fact
  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 set as a subgoal 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 operations 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 do, but do not necessarily detail everything that needs to happen within the production. You will learn the syntax for precise production specification in ACT-R later in this unit.

## 1.2 Creating Knowledge Elements

To create chunks, chunk types, and productions one must issue the necessary ACT-R commands. Because ACT-R commands are Lisp functions they must be enclosed in parentheses to execute them. The first term after the left parenthesis is the command name. That is followed by the details needed for the command and then a right parenthesis. In the following sections we will show how to use the commands to create the knowledge representations in ACT-R.

### 1.2.1 Creating New Chunk Types

To create a new type of chunk like “bird” or “addition fact”, you need to specify a frame for the chunk using the **chunk-type** command. This requires that you specify the name of the chunk type and the names of the slots that it will have. The general chunk type specification looks like this:

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

and here are some examples:

```
(chunk-type bird species color size)
(chunk-type column row1 row2 row3)
```

The first argument to **chunk-type** specifies the name of the new type. In the examples above the names are *bird* and *column*. Each type of chunk also has a number of slots each of which can hold one value. The remaining arguments in the **chunk-type** specification are the names of the slots for that type of chunk.

### 1.2.2 Creating Chunks

The command to create a set of chunks and add them to model’s declarative memory is called **add-dm**. It takes any number of chunk specifications as its arguments. Here is an example from the **count** model we will discuss later:

```
(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 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 you want which is not already used as the name of a chunk as long as it is also a valid Lisp symbol. 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 to refer to the chunk - it is not considered to be a part of the chunk, and can in fact be omitted in which case a new and unique name will be generated for that chunk automatically. The rest of the list is pairs of slot names and initial values. The first pair must be the **isa** slot and the type of the chunk. The **isa** slot is special because every chunk has one. Its value is the type of the chunk, which must be either a type that was defined with **chunk-type** or one of the predefined types, and it cannot be

changed once the chunk is created. The remainder of the slot-value pairs can be specified in any order, and it is not necessary to specify an initial value for every slot of the chunk. If an initial value for a slot is not given, that slot will be empty which is denoted with the Lisp symbol **nil**.

### 1.2.3 Productions

A production is a condition-action pair. The condition (also known as the left-hand side or LHS) specifies a pattern of chunks that must be present in the **buffers** for the production to apply. The action (right-hand side or RHS) specifies some actions to be taken when the production fires.

### 1.2.4 Buffers

Before continuing with productions we need to describe what these buffers are. The buffers are the interface between the procedural memory system in ACT-R and the other components (called modules) of the ACT-R architecture. For instance, the **goal** buffer is the interface to the goal module. Each buffer can hold one chunk at a time, and the actions of a production affect the contents of the buffers. Essentially, buffers operate like scratch-pads for creating, storing, and modifying chunks.

In this chapter we will only be concerned with two buffers -- one for holding the current goal and one for holding information retrieved from the model's declarative memory module. Later chapters will introduce other buffers and modules as well as further clarify the operations of the **goal** and **retrieval** buffers used here.

### 1.2.5 Productions Continued

The general form of 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 that describes what it does. The buffer tests consist of a set of patterns to match against the current buffers' contents. If all of the patterns correctly match, then the production is said to match and it can be selected. It is possible for more than one production to successfully match the current buffer contents. However, among all the matching productions only one will be selected, and that production's actions will be performed. The process of choosing a production from those that match is called conflict resolution, and it will be discussed in detail in later units. For now, what is important is that only one production may fire at a time. After a production fires,

matching and conflict resolution will again be performed and that will continue until the model has finished.

## 1.3 Production Specification

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 the following production that counts from one number to the next:

|                         | English Description                                |
|-------------------------|--|
| (P counting-example     |  |
| =goal>                  | If the goal chunk is                               |
| isa        count        | of the type count                                  |
| state      incrementing | the state slot has the value incrementing          |
| number     =num1        | there is a number we will call =num1               |
| =retrieval>             | and the chunk in the retrieval buffer              |
| isa        count-order  | is of type count-order                             |
| first      =num1        | the first slot has the value =num1                 |
| second     =num2        | and the second slot has a value we will call =num2 |
| ==>                     | Then   |
| =goal>                  | change the goal                                    |
| number     =num2        | to continue counting from =num2                    |
| +retrieval>             | and request a retrieval                            |
| isa        count-order  | of a count-order chunk to                          |
| first      =num2        | find the number that follows =num2                 |
| )                       |  |

### 1.3.1 Production Conditions

The condition of the preceding production specifies a pattern to match to the **goal** buffer and a pattern to match to the **retrieval** buffer:

```
=goal>
  isa        count
  state      incrementing
  number     =num1
=retrieval>
  isa        count-order
  first      =num1
  second     =num2
```

A pattern starts by naming which buffer is to be tested followed by the symbol ">". The names **goal** and **retrieval** specify the goal buffer and the retrieval buffer. It is also required to prefix the

name of the buffer with "=" (more on that later). After naming a buffer, the first test must specify the chunk-type using the isa test and the name of a chunk-type. That may then be followed by any number of tests on the slots for that chunk-type. A slot test consists of an optional modifier (which is not used in any of the tests in this example production), the slot name, and a specification of the value it must have. The value may be either a specific constant value or a variable.

Thus, this part of the first pattern:

```
=goal>
  isa      count
  state    incrementing
```

means that the chunk in the **goal** buffer must be of the chunk-type **count** and the value of its state slot must be the explicit value **incrementing** for this production to match.

The next slot test in the goal pattern involves a variable:

```
number      =num1
```

The "=" prefix in a production is used to indicate a variable. Variables are used in productions to test for general conditions. They can be used for two basic purposes. In the condition they 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. They can also be used to copy values from one slot to another slot in the actions of the production. The name of the variable can be any symbol and should be chosen to help make the purpose of the production clear. A variable is only meaningful within a specific production. The same variable name used in different productions does not have any relation between the two uses. For a variable test to successfully match there must be some value in the slot. An empty slot, indicated with the Lisp symbol **nil**, will not match to a variable in a buffer specification.

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

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

First it tests that the chunk is of type **count-order**. Then it tests the **first** slot of the chunk with the variable **=num1**. Since that variable was also used in the goal test, this is testing that this slot of the chunk in the **retrieval** buffer has the same value as the **number** slot of the chunk in the **goal** buffer. Finally, it tests the **second** slot with a variable called **=num2**. This means that there must be a value in the **second** slot, it cannot be empty, but there are no constraints placed on what that value must be.

In summary, this production will match if the chunk in the **goal** buffer is of type count, the chunk in the **retrieval** buffer is of type count-order, the chunk in the **goal** buffer has the value incrementing in its state slot, the value in the number slot of the **goal** buffer's chunk and the first slot of the **retrieval** buffer's chunk match, and there is some value in the second slot of the chunk in the **retrieval** buffer.

One final thing to note is that **=goal** and **=retrieval**, as used to specify the buffers, are also variables. They will be bound to the chunk that is in the **goal** buffer and the chunk that is in the **retrieval** buffer respectively. These variables for the chunks in the buffers 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.

### 1.3.2 Production Actions

The right-hand side of a production consists of a set of actions that affect the buffers. Here are the actions from the example production again:

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

The actions are specified similarly to the conditions. They state the name of a buffer followed by ">" and then some slot and value specifications. There are three types of actions that can happen to a buffer and they are designated by the character that precedes the name of the buffer.

#### 1.3.2.1 Buffer Modifications

If the buffer name is prefixed with "=" then the action is for the production to immediately modify the chunk currently in that buffer. Thus this action on the **goal** buffer:

```
=goal>
  number      =num2
```

changes the value of the **number** slot of the chunk in the **goal** buffer to the current value of the **second** slot of the chunk in the **retrieval** buffer. This is an instance of a variable being used to copy a value from one slot to another.

### 1.3.2.2 Buffer Requests

If the buffer name is prefixed with a "+", then the action is a request to that buffer's module. Typically this results in the module replacing the chunk in the buffer with a different one, but it could also be a request for the module to make some change to the chunk that is already in the buffer. Each module has its own purpose and handles different types of requests. In later units of the tutorial we will describe modules that can handle visual attention, manual control requests, and some other types of actions.

In this unit, we are dealing only with the declarative memory and goal modules. Requests to the declarative memory module (the module for which the **retrieval** buffer is the interface) are always a request to retrieve a chunk from the model's declarative memory which matches the specification provided. If a matching chunk is found, it will be placed into the **retrieval** buffer.

Thus, this request:

```
+retrieval>
  ISA          count-order
  first        =num2
```

is asking the declarative memory module to retrieve a chunk which is of type count-order and with a **first** slot that has the same value as **=num2**. If such a chunk exists in the declarative memory of the model, then it will be placed into the **retrieval** buffer.

### 1.3.2.3 Buffer Clearing

The third type of action that can be performed on a buffer is to explicitly clear the chunk from the buffer. This is done by placing "-" 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>
```

### 1.3.2.4 Implicit Clearing

In addition to the explicit clearing action one can make, there is also an implicit clearing that will occur for buffers. A request of a module with a "+" action will automatically cause that buffer to be cleared. So, this request from the example production:

```
+retrieval>
  ISA          count-order
  first        =num2
```

results in the **retrieval** buffer being automatically cleared.

## 1.4 ACT-R Models

We will be going through a series of examples to illustrate how a production system like ACT-R's works and to introduce you to the ACT-R environment. All of your work in the ACT-R tutorial will probably involve using the ACT-R environment. The ACT-R environment is a GUI for running, inspecting, and debugging ACT-R models. It can be run with Lisp implementations from multiple vendors in a variety of operating systems or as a standalone application without the need for a Lisp application under Windows or Mac OS X.

Model files for ACT-R are text files that contain Lisp source code with the ACT-R commands to specify how the model works. They can be opened and edited in any application that can operate on text files. If you are running a Lisp with a GUI then that is probably the best tool for opening and editing your models because it will provide lots of support for editing Lisp code, for example, things like matching parentheses and Lisp language reference tools. If you are using a command line Lisp you will need to use some other text editor program, and if you are using the standalone version of the ACT-R environment you may use the text editing facilities it provides (however most text editing programs will provide more capabilities than the ACT-R environment's very basic text tools and they are not recommended unless you have no other options).

To use a model you must load it into a Lisp application that is running the ACT-R software. So, the first thing you need to do is start your Lisp application and load ACT-R. If you have a Lisp with a GUI then there should be an option, typically under the File menu, to load a file, but if you are using a command line Lisp you will need to execute the load command to load the file. The file you need to load is the "load-act-r-6.lisp" file found at the top level of the ACT-R source file distribution. Once that file has loaded you should start the ACT-R environment application. Once it is ready you will connect ACT-R to it by calling the **start-environment** command from Lisp (see the QuickStart.txt file in the docs directory of ACT-R 6 for more details on starting the system and a shortcut for starting the environment in some Lisp & OS combinations).

After ACT-R is loaded and the ACT-R environment is connected you are now ready to load and run ACT-R models. To load a model you can do that directly in your Lisp application just as you loaded ACT-R. Alternatively, you can use the "Load Model" button on the Control Panel of the ACT-R environment. For model files that contain Lisp functions to present an experiment to the model you will see better performance if you compile the model file before loading it. Most Lisp GUIs offer an option called "Compile and Load" which you can use and some Lisps compile all functions by default (consult your Lisp's documentation for specific details).

Once a model has been loaded, you can run it. Models that do not interact with an experiment can be run by calling the ACT-R **run** command. The **run** command requires one parameter, which is the length of simulated time to run the model measured in seconds. Thus, to run a model for 10 simulated seconds one would enter this at the Lisp prompt:

```
(run 10)
```

Now, to put these ideas into action, we will start working with some example models.

## 1.5 The Count Model

The first model is a simple production system 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. It is contained in the file called “count.lisp”. You should now start ACT-R and the ACT-R environment if you have not done so already and load the count model.

If you run the model for 1 second you should see the following output in your Lisp application or the Listener window if you are using a standalone version of ACT-R:

```
> (run 1)
0.000 GOAL SET-BUFFER-CHUNK GOAL FIRST-GOAL REQUESTED 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 in the running of the model. The event shows the time in seconds at which it happened, the module that generated the event and the details of that event. Any output from the model is also shown in the trace. The default trace shows everything that happened in the model, but often that is more detail than is necessary and it is possible to change the level of detail that is displayed in the trace. How to do that is discussed in the unit 1 model code description document. A model code description document accompanies each of the tutorial units and provides more detailed information about the Lisp code and functions used in that unit's models. Those are the documents with “\_exp” on the end of the name e.g. “unit1\_exp”.

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. We will be focusing on the specification of the chunks and productions. The other commands that are used in this unit's models are described in the unit 1 model description document.

### 1.5.1 Chunk-types for the Count model

In the model file you will find the following two specifications for new chunk types used by this model:

```

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

```

The **count-order** chunk type is used for chunks that encode the ordering of numbers. The **count-from** chunk type will be used as the type for the goal chunk of the model and has slots to hold the starting number, the ending number, and the current count so far.

### 1.5.2 Declarative Memory for the Count model

In the model file you will find the initial chunks placed into the declarative memory of the model:

```

(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 are of the type **count-order** and each counting fact connects 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, **first-goal**, is of the type **count-from** and it 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 stated, it will be empty in the chunk **first-goal** which means that it will have the value **nil**.

### 1.5.3 Setting the Initial Goal

The chunk **first-goal** is declared to be the model's current goal (placed into the **goal** buffer) by the command **goal-focus** in the model:

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

The results of that command can be seen in the first line of the trace:

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

The trace shows that the chunk **first-goal** is set to be the chunk in the **goal** buffer by the goal module. It also indicates that this chunk was not requested by a production. For now, that is not an important detail, but we will come back to other instances of that in later units.

Now that we have seen the chunks the model has we will look at the productions that use those chunks to count.

### 1.5.4 The Start Production

The productions are specified with the command **p**, as described earlier. The count model has three productions: **start**, **increment**, and **stop**. The first production that gets selected and fired by the model is the production **start** which can be seen in this part of the trace:

```
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 conflict resolution to determine which productions, if any, match the current contents of the buffers and then choosing one of them. The next line shows that among those that matched, the **start** production was selected.

The third line shows that the selected production tested the chunk in the goal buffer as a condition. The 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 system, and every production will take 50ms between the time it is selected and when it fires.

Now we will look at the details of the **start** production. Here is its definition from the model:

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

On its LHS it 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 checks that the count slot is currently empty i.e. that it has the value **nil**.

On the RHS it performs two actions. The first is to change the value of the count slot of the chunk in the **goal** buffer to be the value bound to **=num1**. The other action is to request that the declarative memory system retrieve a chunk of type **count-order** that has the value which is bound to **=num1** in its **first** slot.

These actions can be seen as the next two lines of the trace:

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

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 **retrieval** buffer that happens because of the +retrieval> request.

The next line 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
```

The next line indicates that the procedural system is now trying to find a new production to fire:

```
0.050    PROCEDURAL           CONFLICT-RESOLUTION
```

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

The following two lines show the completion of the retrieval request by the declarative memory module and then the setting of the **retrieval** buffer to that chunk.

```
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
```

### 1.5.5 The Increment Production

Here is the specification of the **increment** production:

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

```

==>
  =goal>
    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

```

The “-” in front of the slot is the negative test modifier. It means that this production will only match 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**.

The **retrieval** buffer test checks that it has retrieved a count-order chunk with a value of 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>
  count      =num2
+retrieval>
  ISA        count-order
  first      =num2

```

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

The first two actions are very similar to those in the **start** production. It updates the count slot of the goal chunk with the next number as found from the count-order chunk in the **retrieval** buffer and then requests that a count-order chunk be retrieved to get the next number. 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 must be followed by a list of items and those items 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 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 occurs in the output list the specific value to which it was bound in the production will be substituted into the output which is displayed. Thus the reason 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. A retrieval request is made, the **goal** buffer is modified, 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 multiple times until this point in the trace:

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

### 1.5.6 The Stop Production

The final production in the model is **stop**:

```
(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 actions it takes are to again print out the current number and now 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 is another round of conflict resolution. No productions are found to match and no other events of any module are pending at this time (for instance a retrieval 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
```

### 1.5.7 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. Either load the count model if it is not currently loaded or reset it to its initial conditions if it has been loaded. That is done either by pressing the “Reset” button in the Control Panel or by calling the ACT-R command **reset** at the Lisp prompt.

2. Click on the “Stepper” button in the Control Panel to open the Stepper window. In general, this tool will stop the model before every operation it performs. For each action that shows as a line in the trace, the stepper will force the model to wait for your confirmation before taking that action. 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. Each time a production is selected it 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 not discuss until later in the tutorial). When the production is fired it will show the same information except that the production text will have the variables replaced with their bound values. It will also show the details of which chunk is retrieved when there is a retrieval request.

Right now you are going to use a feature of this window that allows you to manually instantiate the productions. That is, you will assign all of the variables the proper values when the production is selected before continuing to the firing of that production. To enable this functionality of the Stepper, click the “Tutor Mode” checkbox at the top of the window.

3. Click on the “Buffer Viewer” button in the Control Panel to bring up a new Buffer viewer 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. You can also use the command **buffer-chunk** to find the names of the chunks in the buffers. Calling it without any parameters will show all of the buffers and the chunks they contain. If you call it with the name of a buffer, for instance, (**buffer-chunk goal**), then it will print out the chunk that is in the named buffer. At this point the buffers are empty, but that will change as the model runs.

4. Now you should run the model for at least 1 second using the run command as shown above. 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 REQUESTED NIL
```

Hitting the “Step” button in the Stepper window will allow that action to occur. You can now inspect the chunk in the **goal** buffer using either the Buffer Viewer or the **buffer-chunk** command.

### 1.5.8 The first-goal-0 Chunk and Buffer Chunk Copying

If you inspect the **goal** buffer you will see that it contains a chunk named **first-goal-0** and not the chunk **first-goal**. When a chunk is placed into a buffer it is always a new copy of the chunk that

goes into the buffer. The name of the chunk that was copied is also shown in the Buffer Viewer (and by the **buffer-chunk** command) in square brackets after the name of the chunk actually in the buffer. The buffers operate as scratch pads for modifying chunks. As long as a chunk is in a buffer it can be manipulated by productions or any of the other modules. However, once it leaves the buffer it can no longer be modified by the model because any attempt to put it back into a buffer where it can be changed will only result in a new copy.

### 1.5.9 Pattern Matching Exercise Continued

5. If you Step past the conflict-resolution event you will come to the first production to match, **Start**. Its structure will be displayed in the Stepper window and all of the variables will be highlighted. Your task is to go through the production rule replacing all of the variables with the values to which they are bound. When you click on a variable a dialog will open in which you can enter its value. You must enter the value for every instance of a variable in the production (including multiple instances of the same variable) before it will allow you to progress to the next production.

Here are the rules for doing this:

- **=goal** will always bind to the name of the current contents of the goal buffer. This can be found with the Buffer viewer or the **buffer-chunk** command.
- **=retrieval** will always bind to the name of the chunk in the retrieval buffer. This can also be found with the Buffer viewer or the **buffer-chunk** command.
- A variable will have the same value everywhere in a production that matches. The bound values are displayed in the Stepper window as you enter them.
- 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 give you the answer.

6. Once the production is completely instantiated, you can fire it by hitting the “Step” button. The Stepper will then advance through the other events of the model as you continue to hit 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. Then, at the risk of too much repetition, you will need to instantiate two instances of the production **Increment**. Then, when the **start** and **end** slots of the goal are equal, the **Stop** production will match and that will be the last one which you need to instantiate.

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 the next model.

## 1.6 The Addition Model

The second example model uses a slightly larger set of count facts to do a somewhat more complicated task. It will do addition by counting up. Thus, given the goal to add 2 to 5 it will count 5, 6, 7, and return the answer 7. You should load the **addition** model in the same way as you loaded the **count** model.

The initial count facts are the same as those used for the **count** model with the inclusion of a fact that encodes 1 follows 0 and those that encode all the numbers up to 10. The chunk type for the goal now has slots to hold the starting number (**arg1**) and the number to be added (**arg2**):

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

There are two other slots in the goal called **count** and **sum** which will be used to hold the results of the counting and the total so far as the model progresses. Here is the initial goal chunk created for the model:

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

Since the **count** and **sum** slots are not specified, they are empty, which is indicated with the default value of **nil**.

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

|       |             |   |
|-------|-------------|---|
| 0.000 | GOAL        | SET-BUFFER-CHUNK GOAL SECOND-GOAL REQUESTED 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       |
| 0.500 | PROCEDURAL  | CONFLICT-RESOLUTION                       |
| 0.500 | -----       | Stopped because no events left to process |

The first thing you will 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 a reduced trace to make it easier to read the sequence of productions that fire. The model code description document for this unit describes how one can change the amount of detail shown in the trace. Sometimes having all the details can be useful for determining what a model is doing and other times a more concise trace is desirable.

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 requests a retrieval of an increment to the sum. **Increment-sum** processes that retrieval and requests a retrieval of an increment to the count. 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 modifies the **goal** to make the model stop.

### 1.6.1 The initialize-addition and terminate-addition Productions

The production **initialize-addition** initializes an addition process whereby the system 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 |       | English Description          |
|------------------------|-------|------------------------------|
| =goal>                 |       | If the goal is               |
| ISA                    | add   | to add the arguments         |
| arg1                   | =num1 | =num1 and                    |
| arg2                   | =num2 | =num2                        |
| sum                    | nil   | but the sum has not been set |
| ==>                    |       | Then                         |
| =goal>                 |       | change the goal              |
| sum                    | =num1 | by setting the sum to =num1  |
| count                  | 0     | and setting the count to 0   |

|             |             |                                   |
|-------------|-------------|-----------------------------------|
| +retrieval> |             | and request a retrieval           |
| isa         | count-order | of a chunk of type count-order    |
| first       | =num1       | for the number that follows =num1 |
| )           |             |                                   |

This production initializes the **sum** slot to be the first digit and the **count** slot to be zero. It requests a retrieval of 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** applies:

| (P terminate-addition |         | English Description              |
|-----------------------|---------|----------------------------------|
| =goal>                |         | If the goal is                   |
| ISA                   | add     | to add                           |
| count                 | =num    | and the count has the same value |
| arg2                  | =num    | as arg2                          |
| sum                   | =answer | and there is a sum               |
| ==>                   |         | Then                             |
| =goal>                |         | change the goal                  |
| count                 | nil     | to stop counting                 |
| )                     |         |                                  |

This production clears the **count** slot of the goal by setting it to **nil** (remember **nil** is the value of an empty slot). This causes the model to stop because other than **initialize-addition**, (which requires that the sum slot be empty) all the other productions require there to be a chunk in the **count** slot. So, after this production fires none of the productions will match the chunk in the **goal** buffer.

### 1.6.2 The increment-sum and increment-count Productions

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

| (P increment-sum |        | English Description                   |
|------------------|--------|---------------------------------------|
| =goal>           |        | If the goal is                        |
| ISA              | add    | to add                                |
| sum              | =sum   | and the sum is =sum                   |
| count            | =count | and the count is =count               |
| - arg2           | =count | and the count has not reached the end |

|             |             |                                    |
|-------------|-------------|------------------------------------|
| =retrieval> |             | and a chunk has been retrieved     |
| ISA         | count-order | of type count-order                |
| first       | =sum        | where the first number is =sum     |
| second      | =newsum     | and it is followed by =newsum      |
| ==>         |             | Then                               |
| =goal>      |             | change the goal                    |
| sum         | =newsum     | so that the sum is =newsum         |
| +retrieval> |             | and request a retrieval            |
| isa         | count-order | of a chunk of type count-order     |
| first       | =count      | for the number that follows =count |
| )           |             |                                    |

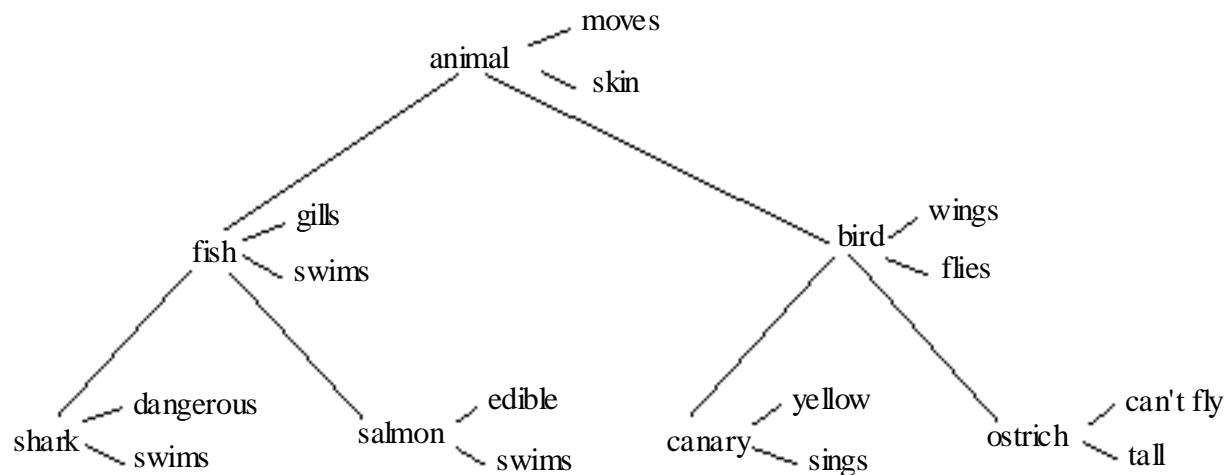
|                    |             |                                  |
|--------------------|-------------|----------------------------------|
| (P increment-count |             | <b>English Description</b>       |
| =goal>             |             | If the goal is                   |
| ISA                | add         | to add                           |
| sum                | =sum        | and the sum is =sum              |
| count              | =count      | and the count is =count          |
| =retrieval>        |             | and a chunk has been retrieved   |
| ISA                | count-order | of type count-order              |
| first              | =count      | where the first number is =count |
| second             | =newcount   | and it is followed by =newcount  |
| ==>                |             | Then                             |
| =goal>             |             | change the goal                  |
| count              | =newcount   | so that the count is =newcount   |
| +retrieval>        |             | and request a retrieval          |
| isa                | count-order | of a chunk of type count-order   |
| first              | =sum        | for the number that follows =sum |
| )                  |             |                                  |

### 1.6.3 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 this example model. Once you have completed that you should move on to the next model.

## 1.7 The Semantic Model

The last example for this unit is the **semantic** model. It contains chunks which encode the following network of categories and properties. It is capable of searching this network to make decisions about whether one category is a member of another category.



### 1.7.1 Encoding of the Semantic Network

All of the links in this network are encoded by chunks of type **property** 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 a true value on the **dangerous** attribute. **p2** encodes that a shark can swim by encoding the value **swimming** on the **locomotion** attribute. **p3** encodes that a shark is a fish by encoding fish as the value on the **category** attribute.

You can inspect the chunks in the **add-dm** command of the model to see how the rest of the semantic network is encoded.

### 1.7.2 Queries about Category Membership

Queries about category membership are encoded by goals of the **is-member** type. There are 3 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 judgment nil)
```

which represents the query to decide if a canary is a bird. The judgment slot is **nil** reflecting the fact that the decision has yet to be made about whether it is true. If you run the model with **g1** in the **goal** buffer you will see the following trace:

|       |             |   |
|-------|-------------|---|
| 0.000 | GOAL        | SET-BUFFER-CHUNK GOAL G1 REQUESTED 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 |

This is among the simplest cases possible and involves only the retrieval of this property

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

for verification of the query. 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**:

|                     | English Description             |
|---------------------|---------------------------------|
| (p initial-retrieve |                                 |
| =goal>              | If the goal is                  |
| ISA is-member       | to judge membership             |
| object =obj         | of =obj                         |
| category =cat       | in the category =cat            |
| judgment nil        | and the judgment has not begun  |
| ==>                 | Then                            |
| =goal>              | change the goal                 |
| judgment pending    | so that the judgment is pending |

|             |          |                                  |
|-------------|----------|----------------------------------|
| +retrieval> |          | and request a retrieval          |
| ISA         | property | of a chunk of type property      |
| object      | =obj     | for the object =obj              |
| attribute   | category | involving the attribute category |
| )           |          |                                  |

|                  |           |                                 |
|------------------|-----------|---------------------------------|
| (P direct-verify |           | <b>English Description</b>      |
| =goal>           |           | If the goal is                  |
| ISA              | is-member | to judge the membership         |
| object           | =obj      | of =obj                         |
| category         | =cat      | in the category =cat            |
| judgment         | pending   | and the judgment is pending     |
| =retrieval>      |           | and a chunk has been retrieved  |
| ISA              | property  | of type property                |
| object           | =obj      | for the object =obj             |
| attribute        | category  | involving an attribute category |
| value            | =cat      | with the value =cat             |
| ==>              |           | Then                            |
| =goal>           |           | modify the goal                 |
| judgment         | yes       | so that the judgment is yes     |
| )                |           |                                 |

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

### 1.7.3 Chaining Through Category Links

A slightly more complex case occurs when the category is not an immediate super ordinate of the queried 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 query is defined in chunk **g2**:

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

One can change the goal to **g2** by the command (**goal-focus g2**). This can be done by editing the model and reloading or by entering (**goal-focus g2**) at the Lisp prompt. Running the model with chunk **g2** as the goal will result in the following trace:

|       |            |  |
|-------|------------|--|
| 0.000 | GOAL       | SET-BUFFER-CHUNK GOAL G2 REQUESTED 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 involves an extra production, **chain-category**, which retrieves the category in the case that an attribute has been retrieved which does not allow a decision to be made. Here is that production:

(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
```

)

### English Description

If the goal is  
to judge the membership  
of =obj1  
in =cat  
and the judgment is pending  
and a chunk has been retrieved  
of type property  
for the object =obj1  
involving an attribute category  
with a value =obj2  
and this is not the same as =cat

Then  
change the goal  
to judge the category membership of =obj2  
and request a retrieval  
of a chunk of type property  
for the object =obj2  
involving the attribute category

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

### 1.7.4 The Failure Case

Now change the goal to the chunk **g3**.

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

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 REQUESTED 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  | CONFLICT-RESOLUTION                       |
| 0.350 | -----       | Stopped because no events left to process |

The production **fail** applies and fires when a retrieval attempt fails. This production uses a condition on the LHS that we have not yet seen.

### 1.7.5 Query Conditions

In addition to testing the chunks in the buffers as has been done in all of the productions to this point, it is also possible to query the state of the buffer or the module which controls it. This is done using a “?” operator instead of an “=” before the name of the buffer. A module may have a number of different queries to which it will respond, but there are some to which all buffers and

modules will always respond. The queries that are always valid are whether there is a chunk in the buffer or not, whether or not that chunk was requested by the procedural module, and for one of three possible states of the module: free, busy, or error. The result of a query will always be either true or false. If any query tested in a production has a result which is false, then the production does not match. Here are examples of the possible queries with respect to the **retrieval** buffer.

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

```
?retrieval>
  buffer      full
```

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

```
?retrieval>
  buffer      empty
```

This query will be true if the chunk in the **retrieval** buffer was requested by a production (which should always be true for the **retrieval** buffer) or false if the chunk was not requested by a production:

```
?retrieval>
  buffer      requested
```

This query will be true if the chunk in the **retrieval** buffer was placed there other than by a request in a production and false if the chunk was the result of a production's request:

```
?retrieval>
  buffer      unrequested
```

This query will be true if the **retrieval** buffer's module (the declarative memory module) is not currently working to retrieve a chunk and false if it is currently working on retrieving a chunk:

```
?retrieval>
  state       free
```

This query will be true if the declarative memory module is working on retrieving a chunk and false if it is not:

```
?retrieval>
  state       busy
```

This query will be true if there was an error in the last request made to the **retrieval** buffer and false if there was no error:

```
?retrieval>
  state      error
```

For retrieval requests, an error means that no chunk could be found that matched the request.

It is also possible to make multiple queries at the same time. For instance this query would check if the module was not currently handling a request and that there was currently a chunk in the buffer:

```
?retrieval>
  state      free
  buffer     full
```

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 retrieving a chunk:

```
?retrieval>
  state      free
or
?retrieval>
  - state    busy
```

### 1.7.6 The fail production

Now, here is the production that fires in response to a category request not being found.

| (P fail     |           | English Description             |
|-------------|-----------|---------------------------------|
| =goal>      |           | If the goal is                  |
| ISA         | is-member | to judge membership             |
| object      | =obj1     | of =obj1                        |
| category    | =cat      | in =cat                         |
| judgment    | pending   | and the judgment is pending     |
| ?retrieval> |           | and the retrieval               |
| state       | error     | has failed                      |
| ==>         |           | Then                            |
| =goal>      |           | change the goal                 |
| judgment    | no        | so that the judgment slot is no |
| )           |           |                                 |

Note the testing for a retrieval 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 that

matches the specification requested, the buffer's state indicates an error. 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 Stepper tool one final time.

### 1.7.7 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 first loaded the **semantic** model there should have been warnings like this displayed:

```
#|Warning: Creating chunk CATEGORY of default type chunk |#  
#|Warning: Creating chunk PENDING of default type chunk |#  
#|Warning: Creating chunk YES of default type chunk |#  
#|Warning: Creating chunk NO of default type chunk |#
```

Lines that begin with ”#|Warning:” are 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 your Lisp application which indicate a problem in the overall syntax or structure of the Lisp code in the file. If you see ACT-R warnings when loading a model you should always check 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.

If there had been a typo in one of the productions however, for instance misspelling pending in one of them as “pneding”, looking at the warnings would have shown something like this:

```
#|Warning: Creating chunk PENDING of default type chunk |#  
#|Warning: Creating chunk PNEDING of default type chunk |#
```

That would provide you with an opportunity to fix the problem before running the model and trying to determine why the production did not fire when expected.

There are many other ACT-R warnings that could be displayed and you should always read them to make sure that there are no serious problems before running the model.

## 1.8 Building a Model

We would like you to now construct the pieces of an ACT-R model on your own. The **tutor-model** file included with the tutorial models 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 addition of two two-digit numbers. Once all of the pieces have been added as described, 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 REQUESTED 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 experiment description text for this unit. So, 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** 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).

### 1.8.1 Chunk-types

The first thing we need to do is define the chunk types that will be used by 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. These chunk types will be created with the **chunk-type** command as described in section 1.2.1.

#### 1.8.1.1 Addition Facts

The first chunk type you will need is one to represent the addition facts. It should be named **addition-fact** and have slots named **addend1**, **addend2**, and **sum**.

#### 1.8.1.2 The Goal Chunk Type

The other chunk type you will need is one to represent the goal of adding two two-digit numbers. It should be named **add-pair**. It must 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**.

After you have created those chunk-types you have completed the chunk type portion of this model. Now it is time to create the chunks that allow the model to perform addition along with an initial goal to do such an addition.

### 1.8.2 Chunks

We are now going to define the chunks that will allow the model to solve the problem  $36 + 47$ . This is done using the **add-dm** command which is described in section 1.2.2.

#### 1.8.2.1 The Addition Facts

You need to add the addition facts to encode the following math facts:

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

They will be of 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 appropriate numbers.

### 1.8.2.3 The Initial Goal

You should now create a chunk called **goal** which encodes that the goal is to add 36+47. 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.

Once you have completed adding the chunk-types and chunks to the model you should be able to load it and inspect the components you have created. To see the chunks you have created you can press the “Declarative Viewer” button on the Control Panel. That will open a declarative memory viewer (every time you press that button a new declarative viewer window will be opened). You can view a particular chunk by clicking on it in the list of chunks on the left of the declarative memory viewer. If you define a lot of chunks it may be difficult to find a particular one in the list. To help in that situation there is a filter at the top of the declarative memory viewer (the recessed button that defaults to saying **none**) that will allow you to specify a particular chunk-type, and only chunks having that chunk-type will be displayed. Try selecting **addition-fact** as the filter. You should now only see the chunks for the addition facts that you created. If you select **none** for the filter, then all of the chunks in declarative memory are displayed.

You can also inspect declarative memory from the Lisp prompt. The command **dm** will print out all of the chunks in declarative memory. You can also specify the name of chunks as parameters to the **dm** command and only those chunks will be printed. The command **sdm** can be used like the filter in the declarative memory viewer. Its parameters are a chunk description (similar to a retrieval request) and it prints out only those chunks from the model’s declarative memory which match that description. For example, (**sdm isa addition-fact**) will print out only those chunks which are of type addition-fact and (**sdm isa addition-fact addend1 3**) will print only the addition facts that have the value **3** in the **addend1** slot.

You are now ready to begin the next section, where you will write productions.

## 1.8.2 Productions

So far, we have been looking mainly at the individual productions in the models. However, production systems get their power through the interaction of the productions. Essentially, one

production will set the condition for another production to fire, and it is the sequence of productions firing that lead to performing the task.

Your task is to write the ACT-R equivalents of the production rules described below in English, which can perform multi-column addition. To do that you will need to use the ACT-R **p** command to specify the productions as described in sections 1.2.5 and 1.3.

Here are the English descriptions of the six productions needed for this task.

#### **START-PAIR**

IF the goal is to add a pair of numbers  
and the ones digits of the pair are available  
but the ones digit of the answer is **nil**  
THEN note in the one-ans slot that you are **busy** computing  
the answer for the ones digit  
and request a retrieval of the sum of the ones digits.

#### **ADD-ONES**

IF the goal is to add a pair of numbers  
and you are **busy** waiting for the answer for the ones digit  
and the sum of the ones digits has been retrieved  
THEN store the sum as the ones answer  
and note that you are **busy** checking the answer for the carry  
and request a retrieval to determine if the sum equals 10  
plus a remainder.

#### **PROCESS-CARRY**

IF the goal is to add a pair of numbers  
and the tens digits are available  
and you are **busy** working on the carry  
and the one-ans equals a value which a retrieval  
finds is the sum of 10 plus a remainder  
THEN make the ones answer the remainder  
and note that the carry is 1  
and note you are **busy** computing the sum of the tens digits  
and request a retrieval of the sum of the tens digits.

#### **NO-CARRY**

IF the goal is to add a pair of numbers  
and the tens digits are available  
and you are **busy** working on the carry  
and the one-ans equals a sum  
and there has been a retrieval failure

THEN note that the carry is **nil**  
 and note you are **busy** computing the sum of the tens digits  
 and request a retrieval of the sum of the tens digits.

#### ADD-TENS-DONE

IF the goal is to add a pair of numbers  
 and you are **busy** computing the sum of the tens digits  
 and the carry is **nil**  
 and the sum of the tens digits has been retrieved  
 THEN note the sum of the tens digits.

#### ADD-TENS-CARRY

IF the goal is to add a pair of numbers  
 and the tens digits are available  
 and you are **busy** computing the sum of the tens digits  
 and the carry is 1  
 and the sum of the tens digits has been retrieved  
 THEN set the carry to nil  
 and request a retrieval of one plus that sum.

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 above, and the correct answer should be encoded in the **ten-ans** and **one-ans** slots of the chunk in the **goal** buffer.

### 1.8.3 Incremental Creation of Productions

It is 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 REQUESTED 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 run 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.

### 1.8.4 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 a command called **whynot**. The **whynot** command can be used to tell you what condition on the LHS of a production is causing it to fail to match. It can be called from the Lisp prompt with the name of a production, or it is also available as a button on the “Procedural Viewer” of the Control Panel. To use the ACT-R environment’s version you should select a production from the list of defined productions in the Procedural Viewer window and then press the “Whynot” button. It will open a window with the details of why the production does not match or print the current instantiation of that production if in fact it does match.

The Stepper is also an important tool for use when debugging a model because it lets you watch everything that the model does. You can also use **whynot**, the Buffer viewer, and the Declarative viewer windows while using the Stepper to better understand what is happening in the model at any specific point in its run.