

Unit 7: Production Rule Learning

In this unit we will discuss how new production rules are learned. As we will see, a model can acquire new production rules by collapsing two production rules that apply in succession into a single rule. Through this process the model will transform knowledge that is stored declaratively into a procedural form. We call this process of forming new production rules **production compilation**.

7.1 The Basic Idea

A good pair of productions for illustrating production compilation is the two that fire in succession to retrieve a paired associate in the **paired** model from Unit 4:

```
(p read-probe
  =goal>
    isa      goal
    state    attending-probe
  =visual>
    isa      text
    value    =val
==>
  +imaginal>
    isa      pair
    probe    =val
  +retrieval>
    isa      pair
    probe    =val
  =goal>
    state    testing
)

(p recall
  =goal>
    isa      goal
    state    testing
  =retrieval>
    isa      pair
    answer   =ans
    ?manual>
    state    free
==>
  +manual>
    isa      press-key
    key      =ans
  =goal>
    state    read-study-item
  +visual>
    isa      clear
)
```

If these two productions fired and retrieved the chunk for the pair of zinc & 9, production compilation would combine these two rules into the following single production:

```
(P PRODUCTION0
  "READ-PROBE & RECALL - PAIR0-0"
  =GOAL>
    ISA GOAL
    STATE ATTENDING-PROBE
  =VISUAL>
    ISA TEXT
    VALUE "zinc"
  ?MANUAL>
    STATE FREE
==>
  =GOAL>
    STATE READ-STUDY-ITEM
  +VISUAL>
    ISA CLEAR
```

```
+MANUAL>
  ISA PRESS-KEY
  KEY "9"
+IMAGINAL>
  ISA PAIR
  PROBE "zinc"
)
```

Essentially, this production combines the work of the two and has built into it the paired associate. In the next two subsections we will describe the general principles used for combining two production rules together and the factors that control how these productions compete in the conflict resolution process.

7.2 Forming a New Production

The basic idea behind forming a new production is to combine the tests in the two conditions into a single set of tests that will recognize when the pair of productions will apply and combine the two sets of actions into a single set of actions that has the same overall effect. Since the conditions consist of a set of buffer tests and the actions consist of a set of buffer transformations (either direct changes or new requests) this can be done largely on a buffer-by-buffer basis. The complications occur when there is a buffer transformation in the action of the first production and either a test of that buffer in the condition of the second production or another transformation of the same buffer in the action of the second production. The productions above illustrate both complications with respect to the **goal** buffer. Because the change to the state slot of the **goal** buffer chunk in the first production is tested as a condition in the second production that test can be omitted from the tests of the compiled production. Then, because that state slot is changed again by the second production, and the compiled production only needs to reproduce the final state of the original two productions, that first goal change can also be omitted from the actions of the compiled production. The result of the overlap in the **goal** buffer is just a simplification of the production rule but in other cases other responses are necessary.

Because different modules use their buffers in different ways the production compilation process needs to be sensitive to those differences. For instance, in the above production we see that the **retrieval** buffer request was omitted from the newly formed production, but the **imaginal** buffer request was not. Thus the production compilation mechanism is built around a set of buffer styles and each buffer is classified as one of the styles. For each style there is a set of rules that specify when two productions that use such a buffer can be combined through compilation, and for each style there is a set of rules for how to combine the uses of a buffer. By default there are five styles to which the default buffers of ACT-R are assigned and we will describe those mechanisms in the following sections. One thing to note is that it is possible to add new styles and to adjust the assignment of buffers to styles, but that is beyond the scope of the tutorial.

7.2.1 Motor Style Buffers

Let us first consider the compilation policy for the motor style buffers. The built in buffers that fit this style are the **manual** and **vocal** buffers. The main distinction of these buffers is that they never hold a chunk. They are used solely for generating actions and they are only tested through queries. If the first production makes a request of one of these buffers on the right hand side then it is not possible to compose it with a second production if that production also makes a request of that buffer or queries it for anything other than state busy. If both productions make a request, then there is a danger of jamming, and any queries that are not checking to see if the module is busy in the second production are probably there to prevent jamming in the future, so also block the compilation.

7.2.2 Perceptual Style Buffers

Now let us consider the compilation policy for the perceptual buffers. Of the included buffers, these are the ones considered perceptual: **visual-location**, **visual**, **aural-location**, and **aural**. These buffers will hold chunks generated by their modules. The important characteristic about them is that those chunks are based on information in the external world, and thus are not guaranteed to result in the same request generating the same result at another time. First, like the motor style buffers, it is not possible to compile two productions which both make requests of the same perceptual style buffer or if the first production makes a request and the second production makes a query for other than state busy of that buffer because of the possibility of jamming. In addition, if the first production makes a request of one of these buffers then it is not possible to compose it with the second production if that production tests the contents of the buffer. This is because of the unpredictable nature of such requests – one does not want to create productions that encapsulate information that is based on external information which may not be valid ever again (at least not for most modeling purposes). The idea is that we only want to create new productions that are “safe”, and by safe we mean that the new production can only match if the productions that it was generated from would match and that its actions are the same as those of its parent productions. Basically, for the default mechanism, we do not want compiled productions to be generated that introduce new errors into the model.

Thus, points where a request is made of a perceptual or motor style buffer are points where there are natural breaks in the compilation process. The standard production compilation mechanisms will not compose a production that makes such a request with a following production that operates on the same buffer.

7.2.3 Retrieval Style Buffer

Next let us consider the compilation policy for the **retrieval** buffer (the only buffer of the retrieval style by default). Because it is an internal buffer (i.e., not subject to the whims of the outside world) it is more predictable and thus offers an opportunity for economy. The interesting opportunity for economy occurs when the first production requests a

retrieval and the second tests for the successful outcome of that retrieval. In this case, one can delete the request and test and instead specialize the two productions -- by replacing throughout the production any variables in the retrieval request with the constants they are bound to based on the chunk that is retrieved. This was what happened in the example production above where the retrieved paired-associate for zinc & 9 was built into the new production0. There is one case, however, where it is not possible to drop out the retrieval request. That is when the first production requests a retrieval and the second does a query for a retrieval error. This cannot be composed because declarative memory grows monotonically and it is not safe to predict that in the future there will be a retrieval error. This suggests that it is preferable, if possible, to write production rules that do not depend on retrieval failures.

7.2.4 Goal and Imaginal Style Buffers

The **goal** and **imaginal** buffers are also internal buffers allowing economies to be achieved. The mechanisms used for these two buffers are very similar, and thus will be described together. The difference between them arises from the fact that the **imaginal** buffer requests take time to complete, and that difference will be described below. First, we will analyze the process for which they are the same and that is broken down into cases based on whether the first production involves a request to the buffer or not.

7.2.4.a First production does not make a request

Let C1 and C2 be the conditions for the buffer in the first and second production and A1 and A2 be the corresponding productions' buffer modification actions for that buffer. Then, the buffer test for the combined production is essentially $C1+(C2-A1)$ where $C2-A1$ specifies those things tested in C2 that were not created in A1. The modification for the combined production is $A2+(A1\sim A2)$ where $(A1\sim A2)$ indicates those things that were in A1 that are not undone by A2. If the second production makes a request, then that can just be kept.

7.2.4.b First production makes a request

This case breaks down into two subcases depending on whether the second production also makes a request.

The second production does not also make a request. In this case the second production's buffer test can be deleted since its satisfaction is guaranteed by the first production. Let C1 be the buffer condition of the first production, A1 be the buffer modification action of the first production, N1 be the new request in the first production, C2 be the buffer condition in the second production and A2 be the buffer modification of the second production. Then the buffer test of the composed production is just C1, the goal modification is just A1, and the new goal request is $A2+(N1\sim A2)$.

The second production also makes a request. In this case the two productions cannot be compiled because this would require either skipping over the intermediate request,

which would result in a chunk not being created in the new production which was generated by the initial two productions, or making two requests to the buffer in one production which could lead to jamming the module.

7.2.4.c *Difference between goal and imaginal*

The difference between the two comes down to the use of queries. Because the imaginal module's requests take time one typically needs to make queries to test whether it is free or busy whereas the goal module's requests complete immediately and thus the state is never busy. So, for goal style buffers production compilation is blocked by any requests in either production because that represents an unusual situation and is thus deemed unsafe. For imaginal style buffers however queries are allowed under the same restrictions as for motor style buffers – if the first production makes a request and the second has a query of that buffer they can only be combined if the query is for state busy.

7.3 Utility of newly created productions

So far we have discussed how production rules are created but not how they are selected. When a new production, which we will call **New**, is composed from old productions, which we will call **Old1** and **Old2** and which fired in that order, it is the case that whenever **New** could apply **Old1** could also apply (Note because **New** might be specialized it does not follow that whenever **Old1** could apply **New** could also apply.) The choice between **New**, **Old1**, and whatever other productions might apply will be determined by their utilities as was discussed in the previous unit. These utilities were either set in the model with the spp command, or were learned on the basis of rewards.

A newly learned production **New** will initially receive a utility of zero by default (that can be changed with the :nu parameter). Assuming **Old1** has a positive value, this means that **New** will almost always lose in conflict resolution with **Old1**. However, each time **New** is recreated from **Old1** and **Old2**, its utility is updated with a reward equal to the current utility of **Old1**, using the same learning equation as discussed in the previous unit:

$$U_i(n) = U_i(n-1) + \alpha[R_i(n) - U_i(n-1)] \quad \text{Difference Learning Equation}$$

As a consequence, even though **New** may not fire initially, its utility will gradually approach the utility of **Old1**. Once the utility of **New** and **Old1** are close enough, **New** will occasionally be selected because of noise. Once **New** is selected itself it will receive a reward like any other production which fires, and its utility can surpass **Old1**'s utility if it is better (it is usually a little better because it typically leads to rewards faster since it saves a rule firing and often a retrieval request).

7.4 Learning from Instruction

Generally, production compilation allows a problem to be solved with fewer productions over time and therefore performed faster. In addition to this speed-up, production compilation results in the drop-out of declarative retrieval as part of the task performance. As we saw in the example in the first section, production rules are produced that just "do it" and do not bother retrieving the intervening information. The classic case of where this applies in experimental psychology is in the learning of experimental instructions. These instructions are told to the participant and initially the participant needs to interpret these declarative instructions. However, with practice the participant will come to embed these instructions into productions that directly perform the task. These productions will be like the productions we normally write to model participant performance in the task. Essentially these are productions that participants learn in the warm-up phase of the experiment. The **paired-learning** model for this assignment contains an example of a system that interprets instructions about how to perform a paired associate task and learns productions that do the task directly.

In the model we use the following chunks to represent the understanding of the instructions for the paired associate task (in some of our work we have built productions that read the instructions from the screen and build these chunks but we are skipping that step here to focus on the mechanisms of this unit):

1. (op1 isa operator pre start action read arg1 create post stimulus-read)
2. (op2 isa operator pre stimulus-read action associate arg1 filled arg2 fill post recalled)
3. (op3 isa operator pre recalled action test-arg2 arg1 respond arg2 wait)
4. (op4 isa operator pre respond action type arg2 response post wait)
5. (op5 isa operator pre wait action read arg2 fill post new-trial)
6. (op6 isa operator pre new-trial action complete-task post start)

These are represented as operators that indicate what to do in various states during the course of a paired-associate trial. They consist of a statement of what that state is in the **pre** slot and what state will occur after the action in the **post** slot. In addition, there is an **action** slot to specify the action to perform and two slots, **arg1** and **arg2**, for holding possible arguments needed during the task execution. So to loosely translate the six operators above:

1. Read the word and create an encoding of it as the stimulus
2. Try to retrieve an associate to the stimulus
3. Test whether an item has been recalled and if it has not then just wait
4. If an item has been recalled type it and then wait
5. Store the response you read with the stimulus
6. This trial is complete so start the next one

The model uses a chunk of type task in the **goal** buffer to maintain a current state and sub step within that state and a chunk of type args in the **imaginal** buffer to hold the items

relevant to the current state. For this task, the arguments are the stimulus and probe for a trial.

The model can retrieve operators and apply them to the current state. In more complicated models we have to deal with things like operator failure but in this simple model we really just need one production rule which is:

```
(p retrieve-operator
  =goal>
    isa    task
    state  =state
    step   ready
==>
  +retrieval>
    isa    operator
    pre    =state
  =goal>
    step   retrieving-operator)
```

This production requests the retrieval of an operator relevant to the current state (=state).

The actions (read, associate, test-arg2, type, test-screen-change, complete-task) are all general actions not specific to a paired associate task. We assume that the participant knows how to do these things going into the experiment. This amounts to assuming that there are productions for processing these actions. For instance, the following two productions are responsible for reading an item and creating a chunk in the **imaginal** buffer which encodes the item into the **arg1** slot of that chunk:

```
(p read-arg1
  =goal>
    isa      task
    step     retrieving-operator
  =retrieval>
    isa      operator
    action   read
    arg1     create
    post     =state
  =visual-location>
    isa      visual-location
  ?visual>
    state    free
==>
  +imaginal>
    isa      args
    arg1     fill)
```

```

+visual>
  isa      move-attention
  screen-pos =visual-location
=goal>
  step      attending
  state     =state)

(p encode-arg1
  =goal>
    isa      task
    step      attending
  =visual>
    isa      text
    value     =val
  =imaginal>
    isa      args
    arg1      fill
==>
  =imaginal>
    arg1      =val
  =goal>
    step      ready)

```

The first production responds to the retrieval of the operator and requests an encoding of the item. It also changes the state in the goal to the operator's post state. The second production encodes the word and sets the goal to be ready to retrieve the operator relevant to the next state.

The **paired-learning** model responds to the same task as the **paired** model you had for Unit 4. However, rather than having specific productions for doing the task it interprets these operators that represent the instructions for doing this task. For reference, here is the data that is being modeled again:

Trial	Accuracy	Latency
1	.000	0.000
2	.526	2.156
3	.667	1.967
4	.798	1.762
5	.887	1.680
6	.924	1.552
7	.958	1.467
8	.954	1.402

The model can be run either with production compilation on or off. To run it with production compilation off, set the **:ep1** parameter to **nil**. The following is a run without production compilation:

? (paired-experiment 10)

Latency:

CORRELATION: 0.989

MEAN DEVIATION: 0.293

Trial	1	2	3	4	5	6 7	8
	0.000	2.354	2.216	2.024	1.938	1.944	1.866 1.771

Accuracy:

CORRELATION: 0.996

MEAN DEVIATION: 0.047

Trial	1	2	3	4	5	6 7	8
	0.000	0.435	0.645	0.780	0.850	0.855	0.945 0.910

When it is run with :epl t, the following is the result:

? (paired-experiment 10)

Latency:

CORRELATION: 0.997

MEAN DEVIATION: 0.143

Trial	1	2	3	4	5	6 7	8
	0.000	2.339	2.118	1.967	1.739	1.718	1.509 1.582

Accuracy:

CORRELATION: 0.996

MEAN DEVIATION: 0.045

Trial	1	2	3	4	5	6 7	8
	0.000	0.445	0.660	0.755	0.835	0.895	0.895 0.955

As can be seen, whether production compilation is off or on has relatively little effect on the accuracy of recall but turning it on greatly increases the speed-up over trials in recall time. This is because we are cutting out productions and retrievals.

If you set the :pct (production compilation trace) parameter to t (and you will also need to set :v to t) you will see the system print out the new productions as they are compiled or the reason why two productions could not be compiled. For instance, the following is a fragment of the trace when we executed the command (paired-task 1 1) to study one paired-associate for 1 trial with production compilation turned on.

```

0.400    PROCEDURAL          PRODUCTION-FIRED RETRIEVE-OPERATOR
Production Compilation process started for RETRIEVE-OPERATOR
  Production ENCODE-ARG1 and RETRIEVE-OPERATOR are being composed.
  New production:

```

```

(P PRODUCTION1
  "ENCODE-ARG1 & RETRIEVE-OPERATOR"
  =GOAL>
    ISA TASK
    STEP ATTENDING
    STATE =STATE
  =IMAGINAL>
    ISA ARGS
    ARG1 FILL

```

```

=VISUAL>
  ISA TEXT
  VALUE =VAL
==>
=IMAGINAL>
  ARG1 =VAL
=GOAL>
  STEP RETRIEVING-OPERATOR
+RETRIEVAL>
  ISA OPERATOR
  PRE =STATE
)
Parameters for production PRODUCTION1:
:utility    NIL
:u    0.000
:at  0.050
:reward    NIL

```

The production that was learned, **Production1**, is a compilation of two of the original productions:

```

(p encode-arg1
  =goal>
    isa      task
    step     attending
  =visual>
    isa      text
    value    =val
  =imaginal>
    isa      args
    arg1     fill
  ==>
    =imaginal>
      arg1    =val
    =goal>
      step    ready
)

(p retrieve-operator
  =goal>
    isa  task
    state =state
    step ready
  ==>
    +retrieval>
      isa  operator
      pre  =state
    =goal>
      step  retrieving-operator
)

```

The first production, **Encode-arg1**, encodes the stimulus, and sets the goal to retrieve the next operator. This is followed by **Retrieve-operator**, which makes the retrieval request. The compiled production is particularly straight forward. Its condition is just the condition of the first production plus the check for the state slot in the goal of the second production, and its action combines the actions of the two.

It is worth understanding how the parameters of this new production are calculated. The value of α is 0.2 (the default). When the production is first created, its utility is set to zero (the default). The utilities of the initial rules in the system are all set to 10 (using the `riu` parameter which sets the starting utility for all of the initial productions), so a value of zero means that it will almost certainly lose the competition with the parent rule the next time it might be applicable. However, each time it is recreated, it receives a reward which is the same as the utility of the first parent rule. Suppose that when the parent fires the next time, and the new rule is recreated, the first parent rule has a utility of 15. The utility of the new rule is then updated:

$$\begin{aligned} U_i(n) &= U_i(n-1) + \alpha[R_i(n) - U_i(n-1)] \\ &= 0 + .2(15 - 0) \\ &= 3 \end{aligned}$$

A utility of 3 is still not sufficient to be selected in competition with a production of utility 15. Thus it will need to be recreated a number of times before it will become possible to be chosen in conflict resolution. The speed of this learning is determined by the setting of α . If it is set to 1, productions will typically get very good values immediately and be tried on the first opportunity. If you do that and run (do-experiment 1 10) you will discover in just 3 trials it is selecting and firing newly learned productions which are then also going through production compilation:

```

20.437      PROCEDURAL      PRODUCTION-FIRED RETIREVE-ASSOCIATE
Production Compilation process started for RETIREVE-ASSOCIATE
Production PRODUCTION1 and RETIREVE-ASSOCIATE are being composed.
New production:

(P PRODUCTION20
  "PRODUCTION1 & RETIREVE-ASSOCIATE - OP2"
  =GOAL>
    ISA TASK
    STATE STIMULUS-READ
    STEP ATTENDING
  =IMAGINAL>
    ISA ARGS
    ARG1 FILL
  =VISUAL>
    ISA TEXT
    VALUE =VAL
  ==>
  =IMAGINAL>
    ARG1 =VAL
    ARG2 FILL
  =GOAL>
    STATE RECALLED

```

```

        STEP RETRIEVING-RESPONSE
+RETRIEVAL>
        ISA ARGS
        ARG1 =VAL
)
Parameters for production PRODUCTION20:
:utility    NIL
:u    0.000
:at    0.050
:reward    NIL

```

After just a couple more trials we will start to find productions that are the composition of multiple previously composed productions and it will very rapidly end up with a production like this:

```

70.955    PROCEDURAL                PRODUCTION-FIRED PRODUCTION37
Production Compilation process started for PRODUCTION37
Production PRODUCTION2 and PRODUCTION37 are being composed.
New production:

(P PRODUCTION54
  "PRODUCTION2 & PRODUCTION37 - ARGS0-0"
  =GOAL>
    ISA TASK
    STATE STIMULUS-READ
    STEP READY
  =IMAGINAL>
    ISA ARGS
    ARG1 "zinc"
  ==>
  =IMAGINAL>
    ARG2 "9"
  =GOAL>
    STATE RESPOND
    STEP READY
)

```

This production basically types 9 in response to the stimulus zinc. However, with normal settings of α , there are not near enough trials to get to this level of automaticity.

7.5 Assignment

Your assignment is to make a model that learns the past tense of verbs in English. The learning process of the English past tense is characterized by the so-called U-shaped learning in the learning of irregular verbs. That is, at a certain age children inflect irregular verbs like “to break” correctly, so they say “broke” if they want to use the past tense. But at a later age, they overgeneralize, and start saying “brokek”. At an even later stage they again inflect irregular verbs correctly. Some people, such as Pinker and Marcus, interpret this as evidence that a rule is learned to create regular past tense (add “ed” to the stem). According to Pinker and Marcus, after this rule has been learned, it is overgeneralized so that it will also produce regularized versions of irregular verbs.

Part of the model is already given in the file `past-tense`. The assignment is to make a model that learns both the regular rule for the past tense, and particular rules for particular irregular verbs. So eventually it should learn rules like:

IF the goal is to make the past tense of a verb
THEN copy that verb and add `-ed`

IF the goal is to make the past tense of the verb have
THEN the past tense is had

The code that is provided does two things. It adds correct past tenses to declarative memory, reflecting the fact that a child hears and then encodes correct past tenses in the environment. It also creates goals which indicate to the model that it should generate the past tense of a verb found in the **imaginal** buffer and then runs the model to generate one. The model will be given two correct past tenses for every one that it must generate.

Here are examples of correctly formed past tenses:

```
PAST-TENSE1
  isa past-tense
  verb have
  stem had
  suffix blank
```

is a correct encoding of the irregular verb have and:

```
PAST-TENSE234
  isa past-tense
  verb use
  stem use
  suffix ed
```

is a correct encoding of the regular verb use.

At the start of the model's run it will have a chunk in the goal buffer which looks like this:

```
GOAL332
  isa goal
  status start
```

and a chunk in the imaginal buffer which looks like this:

```
PAST-TENSE102
  isa past-tense
  verb some-verb
  stem nil
  suffix nil
```

where the verb slot holds the verb for which the model must produce a past tense. The model has to fill in the stem and suffix slots of the chunk in the **imaginal** buffer to indicate the past tense form of the verb and then set the state slot of the chunk in the **goal** buffer to done. Once the state slot is set to done, one of the three production rules provided with the model will fire to simulate the final encoding and “use” of the word, each of which has a different reward. There are three possible cases:

- An irregular inflection, which corresponds to a suffix that is marked explicitly as blank. This use has the highest reward, because irregular verbs tend to be short.
- A regular inflection, in which the stem is the same as the verb and the suffix is ed. This has a slightly lower reward.
- Non-inflected in which both the stem and suffix are still nil. The non-inflection case applies when the model cannot come up with a past tense at all, either because it has no example to retrieve or no rule or strategy to come up with anything else. The non-inflection solution receives the lowest reward because the past tense would have to be indicated by some other method, for example by adding “yesterday” or some other explicit reference to time.

One important thing to notice is that all three solutions receive a reward. The model receives no feedback as to whether the past tenses it produces are correct – any past tense is considered a success and rewarded. The only feedback it receives is the correctly constructed verbs that it hears from the environment.

You can run the model with the **past-tense** command. It takes as an argument the number of words you want the model to generate:

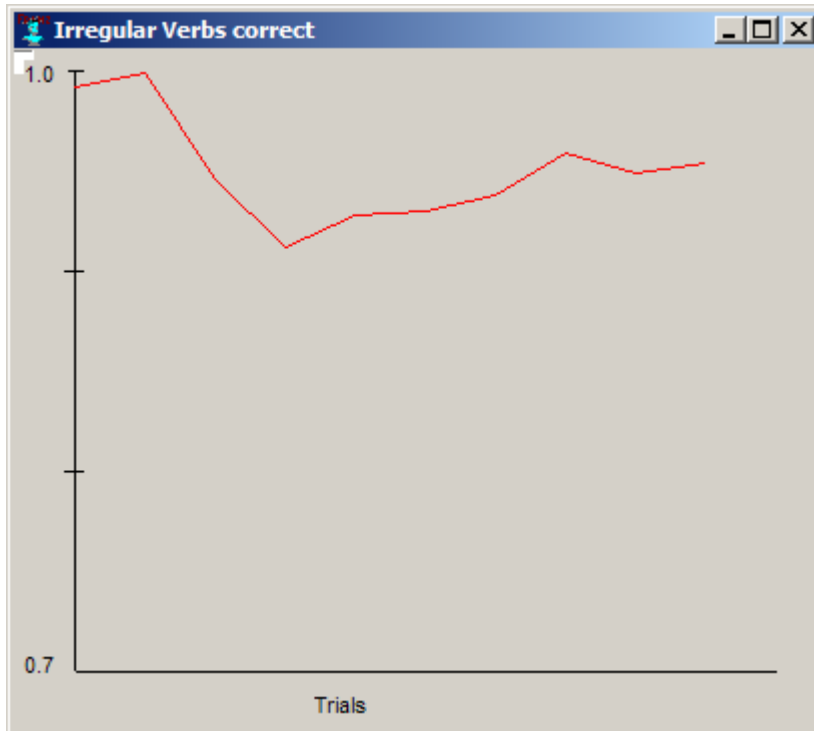
```
(past-tense 5000)
```

As keyword parameters you can specify whether or not you want ACT-R to be verbose (i.e. set the :v parameter to **t**) or whether ACT-R should continue with the run you started in an earlier **past-tense** call. To make the model verbose you would add “:v t” to the call to past-tense and to continue you would add “:cont t”. Thus, if you wanted the model to continue running for 1000 more verbs you would call this:

```
(past-tense 1000 :cont t)
```

During the run, the simulation will display four numbers in a row, reflecting the results of the last 100 verbs generated. The first number is the proportion correct of irregular verbs. The second number is the proportion of irregular verbs that are inflected regularly. An increase in this number indicates a regular rule is active i.e. irregular verbs are having “ed” added to them. The third number is the proportion of irregular verbs that are not inflected at all. The fourth number is the proportion of inflected irregular verbs that are inflected correctly (the non-inflected verbs are not counted for this measure). It is in this last column that you should see a U-shape.

It usually requires more than 5000 trials to see the effect (often 15000~20000 trials are necessary). The `:cont` (continue) option in the **past-tense** function allows you to run more trials without resetting the model. After the model is done, the **report-irreg** function gives a report where results are summarized for 1000 trials at a time. The 100 trial summaries displayed during the **past-tense** function run are really only there to make sure the model is still doing things, and in what direction the results are going. If you have loaded the ACT-R environment then you can pass `t` as a parameter to the **report-irreg** function to have it generate a graph of the data. What you are looking for from the model is a graph that looks something like this:



It starts out with a high percentage correct, dips down, and then goes back up and stays high from that point on. That is the U-shaped learning result.

This model differs from other models in the tutorial in that it does not model a particular experiment, but rather some long term development. This has a couple of consequences for the model. One of those is that using perceptual/motor modules does not contribute much to the objective of the model. Thus things like the "hearing" of past tenses and the eventual generation of the verb in speech are not modeled for the purpose of this exercise. It could be modeled, but it is not what the model and exercise are about. Therefore explicitly adding already processed perceived past tenses to declarative memory and just adding differing rewards for generation of certain classes of verb tenses serves as a reasonable compromise.

The other consequence is that runs of the model may differ considerably. On the one hand this is not so bad, as children also differ with respect to U-shaped learning. One reason for the relative unpredictability is the fact that this simulation runs with a very

limited vocabulary (extending the vocabulary results in a model that runs extremely slowly which is not beneficial as an exercise), but the effect of the noise in the model also has an impact that can create noticeable effects over the long term running of the model. This also makes comparing this model to data difficult, and hard data on the phenomenon are scarce, although the phenomenon of the U-shape is reported often. A few children have been followed in a longitudinal study, and there is a spreadsheet included with the unit materials (data.xls) that shows those results for comparison.

In terms of the assignment, the objective is to write a model that learns the appropriate productions for producing past tenses. There is no parameter adjustment or data fitting required. The key to a successful model is to implement both a retrieval strategy and a simple analogy strategy. The model can either remember a correct past tense or the model attempts to generate a past tense based on another retrieved verb. These should be competing strategies, and only one applied on any given attempt. If the chosen strategy fails to produce a result the model should “give up” and not inflect the verb. The reason for doing that is that language generation is a rapid process and not something for which a lot of time per word can be allocated.

The productions you write should make no explicit reference to either *ed* or *blank* because that is what the model is to eventually learn, i.e., you do not write a production that says *add ed*, but through the compilation mechanism such a production is created. Although the experiment code is only outfitted with a limited set of words, the frequency that the words are presented to the model is in accordance with the frequency they appear in real life. If your model learns the proper productions it should generate the U-shaped learning automatically, but not necessarily on every run. Unlike the other models in the tutorial, there is a fairly small set of “good” solutions to this task which will result in the generation of the U-shaped learning because your model’s starting productions will need to result in the learning of specific productions over time to work correctly.

One important thing to note about your model is that it must set the state slot of the chunk in the goal buffer to *done* each trial so that one of the provided productions will fire and propagate a reward – whether it has generated a past-tense or not. If it does not do so, then there will be no reward propagated to promote the production parameter learning for that trial and the reward from a later trial will be propagated back to the productions on a later trial. That later reward will be very negative because there are 200 seconds between trials, and that will make it very difficult, if not impossible, to produce the U-shaped learning. Essentially this represents the model saying something every time it tries to produce a past-tense while speaking.