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Introduction

– overview of the book, intended audience, getting started (installation instructions etc.)

1.1 Using pyactr – people familiar with Python

If you are familiar with Python, you can install `pyactr` (the Python package that enables ACT-R) and proceed to Chapter 2. `pyactr` is a Python 3 package and can be installed using pip (for Python 3):

```
$ pip3 install pyactr
```

Alternatively, you can download the package here: https://github.com/jakdot/pyactr and follow the instructions there to install the package.

If you are not familiar with Python, you should consider the steps below.

1.2 Using pyactr – beginners

`pyactr` is a package in Python 3. To get started, you should consider a web-based service for Python 3 like `PythonAnywhere`. In this type of services, computation is hosted on separate servers and you don't have to install anything on your computer (of course, you'll need Internet access). If you find you like working with Python and `pyactr`, you can install them on your computer at a later point together with a good text editor for code – or install an integrated desktop environment (IDE) for Python – a common choice is `anaconda`, which comes with a variety of ways of working interactively with Python (IDE with Spyder as the editor, `ipython` notebooks etc.). But none of this is required to run `pyactr` and the code in this book.

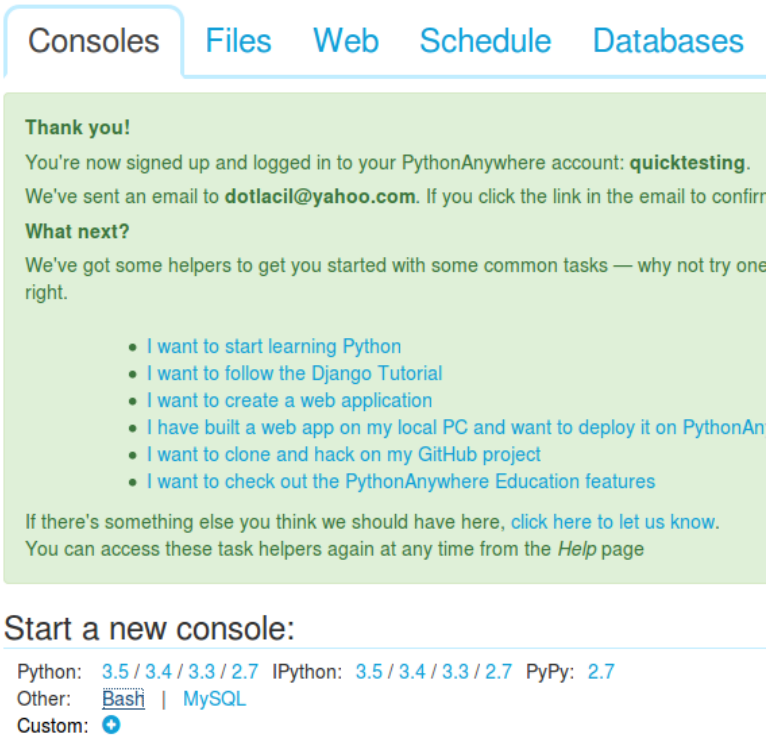
a. Go to www.pythonanywhere.com and sign up there.

b. You'll receive a confirmation e-mail. Confirm your account.

c. Log into your account on www.pythonanywhere.com.

d. You should see a window like the one below. Click on Bash (below "Start a new Console").

Figure 1.1: Opening Bash in PythonAnywhere.



e. In Bash, type:

```
$ pip3 install --user pyactr
```

This will install `pyactr` in your Python account (not on your computer).

f. Go back to Consoles. Start Python by clicking on any version higher than 3.2.

g. A console should open. Type:

```
import pyactr
```

If no errors appear, you are set and can proceed to Chapter 2.

Throughout the book, we will introduce and discuss various ACT-R models coded in Python. You can either type them in line by line or even better, load them as files in your session on PythonAnywhere. Scripts are uploaded under the tab Files. You should be aware that the free account of PythonAnywhere allows you to run only two consoles, and there is a limit on the amount of CPU you might use per day. The limit should suffice for the tutorials but if you find this too constraining, you should consider installing Python (Python 3) and `pyactr` on your computer and running scripts directly there.

Chapter 2

Basics of ACT-R

2.1 Introduction

ACT-R is a cognitive architecture. It is a theory of the structure of the brain that explains and predicts human cognition. The theory of ACT-R has been implemented in several programming languages, including Java (jACT-R, Java ACT-R), Swift (PRIM), Python2 (ccm). The canonical implementation has been created and is maintained in Lisp. In this book, we will use a novel Python (Python3) implementation (`pyactr`). This implementation is very close to the official implementation in Lisp, so once you learn it, you should be able to transfer your skills very quickly to code models in Lisp ACT-R if you wish to do that. At the same time, since Python is currently much more widespread than Lisp, coding parts that do not directly pertain to the ACT-R model (like data manipulation and data munging, interaction with environment etc.) are much better supported than the same tasks in Lisp. In that way, the programming language stands less in a way of your learning ACT-R than it does in case of Lisp, and you can fully focus on learning nuts and bolts of the cognitive models.

This book and the models we build and discuss are not intended as a reference manual for ACT-R. For learning theories of the model, rather than programming in the model itself, consider (Anderson, 1990; Anderson and Lebiere, 1998; Anderson et al., 2004; Anderson, 2007, a.o.). The main goal of this book is to take a hands-on approach to introducing ACT-R by constructing models that solve (or attempt to solve) linguistic problems. We will mix theoretical notes and `pyactr` code.

In general, we will display python code and its associated output in numbered examples and / or numbered blocks.

For example, when we want to discuss the code, we will display it as:

(1)
```
2 + 2 == 4          1
3 + 2 == 6          2
```

Note the numbers on the left – we can use them to refer to specific lines of code, e.g.: the equality in (1), line `1` is true, while the equality in (1), line `2` is false. We will sometime also include in-line Python code, displayed like this: `2 + 2 == 4`.

When we want to discuss both the code and its output, we will display it in the same way it would appear in your interactive Python interpreter, for example:

```
[py1] >>> 2 + 2 == 4                                                    1
      True                                                             2
      >>> 3 + 2 == 6                                                   3
      False                                                            4
```

Once again, all lines are numbered (both the Python code and its output) so that we can refer back to it.

2.2 Why do we care about ACT-R, and cognitive architectures and modeling in general

Linguistics is part of the larger field of cognitive science. So the answer to this question is one that applies to cognitive science in general. Here's one recent version of the argument, taken from chapter 1 of Lewandowsky and Farrell (2010). The argument is an argument for *process* models as the proper scientific target to aim for (roughly, models of human language performance), rather than *characterization* models (roughly, models of human language competence).

Both of them are better than simply *descriptive* models, "whose sole purpose is to replace the intricacies of a full data set with a simpler representation in terms of the model's parameters. Although those models themselves have no psychological content, they may well have compelling psychological implications. [Both characterization and process models] seek to illuminate the workings of the mind, rather than data, but do so to a greatly varying extent. Models that characterize processes identify and measure cognitive stages, but they are neutral with respect to the exact mechanics of those stages. [Process] models, by contrast, describe all cognitive processes in great detail and leave nothing within their scope unspecified. Other distinctions between models are possible and have been proposed [...], and we make no claim that our classification is better than other accounts. Unlike other accounts, however, our three classes of models map into three distinct tasks that confront cognitive scientists. Do we want to describe data? Do we want to identify and characterize broad stages of processing? Do we want to explain how exactly a set of postulated cognitive processes interact to produce the behavior of interest?" (Lewandowsky and Farrell, 2010, 25)

In more detail: "Like characterization models, [the power of process models] rests on hypothetical cognitive constructs, but by providing a detailed explanation of those constructs, they are no longer neutral. [...] At first glance, one might wonder why not every model belongs to this class. After all, if one can specify a process, why not do that rather than just identify and characterize it? The answer is twofold. First, it is not always possible to specify a presumed process at the level of detail required for [a process] model [...] Second, there are cases in which a coarse characterization may be preferable to a detailed specification. For example, it is vastly more important for a weatherman to know whether it is raining or snowing, rather than being confronted with the exact details of the water molecules' Brownian motion. Likewise, in psychology [and linguistics!], modeling at this level has allowed theorists to identify common principles across seemingly disparate areas. That said, we believe that in most instances, cognitive scientists would ultimately prefer an explanatory process model over mere characterization." (Lewandowsky and Farrell, 2010, 19)

2.3 Knowledge in ACT-R

There are two types of knowledge in ACT-R: declarative knowledge and procedural knowledge (see also Newell 1990).

The declarative knowledge represents our knowledge of facts. For example, if one knows what the capital of the Netherlands is, this would be represented in one's declarative knowledge.

Procedural knowledge is knowledge that we display in our behavior (cf. Newell 1973). It is often the case that our procedural knowledge is internalized, we are aware that we have it but we would be hard pressed to explicitly and precisely describe it. Driving, swimming, riding a bicycle are examples of procedural knowledge. Almost all people who can drive / swim / ride a bicycle do so in an automatic way. They are able to do it but they might completely fail to describe how exactly they do it when asked. This distinction is closely related to the distinction between explicit ('know that') and implicit ('know how') knowledge in analytical philosophy (see Ryle 1949 and Polanyi 1967; see also Davies 2001 and references therein for more recent discussions).

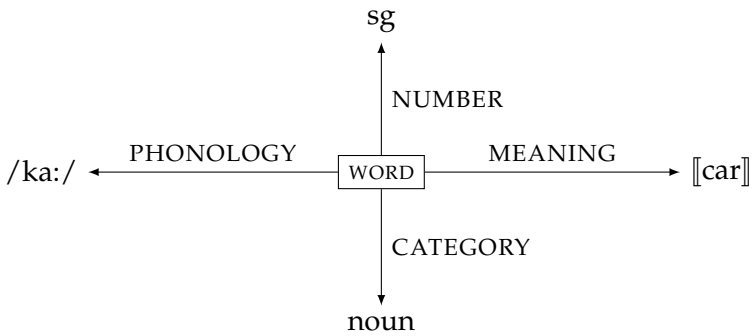
The two parts of knowledge in ACT-R are represented in two very different ways. The declarative knowledge is instantiated in chunks. The procedural knowledge is instantiated in production rules, or productions for short.

2.3.1 Representing declarative knowledge: chunks

Chunks are lists of attribute-value pairs, familiar to linguists from phrase structure grammars (e.g., LFG and HPSG). However, in ACT-R, we use the term *slot* instead of *attribute*. For example, we might think of one's knowledge of the word *car* as a chunk of type WORD with the value /ka:/ for the slot *phonology*, the value ⟦car⟧ for the slot *meaning*, the value noun for the slot *category* and the value sg for the slot *number*.

The slot values are the primitive elements /ka:/, ⟦car⟧, noun and sg, respectively. Chunks are boxed, whereas primitive elements are simple text. A simple arrow (→) signifies that the chunk at the start of the arrow has the value at the end of the arrow in the slot with the name that labels the arrow.

(2)



The graph representation will be useful when we introduce activations and more generally, ACT-R subsymbolic components. The same chunk can be represented as an attribute-value matrix (AVM), and we'll overwhelmingly use AVM representations from now on.

(3)
$$\text{WORD}\begin{bmatrix}\text{PHONOLOGY:} & /\text{ka:}/\\ \text{MEANING:} & [\![\text{car}]\!]\\ \text{CATEGORY:} & \text{noun}\\ \text{NUMBER:} & \text{sg}\end{bmatrix}$$

2.3.2 Representing procedural knowledge: productions

A production is an if-statement. It describes an action that takes place if the if-part is satisfied. For example, agreement on a verb can be (abstractly) expressed as follows: IF subject number in currently constructed sentence is sg THEN verb number in currently constructed sentence is sg. Of course, this is only half of the story – another rule would state: IF subject number in currently constructed sentence is pl THEN verb number in currently constructed sentence is pl. To repeat the basic intuition about the construction of these rules: productions specify conditions (the if-part of the statement); if these conditions are true, then actions take place (the THEN part of the statement).

Sticking with the example in the previous paragraph, it might look like a roundabout way of specifying agreement. Could we not state that the verb has the same number that the subject has? In fact, we can, if we use variables. Variables are assigned their value when they appear on the left side of a production. The variable keeps its value inside a rule (i.e., a rule is the scope for any variable assignment). Given that (and given the convention that variables are signaled in ACT-R using '='), we could write: IF subject number in currently constructed sentence is =x THEN verb number in currently constructed sentence is =x.

2.4 Using `pyactr`

After this brief introduction, we will continue by combining the theoretical part of ACT-R with discussing how it is implemented in `pyactr`. We will begin with describing details of declarative knowledge in ACT-R and its implementation in `pyactr`. After that we turn to the discussion of modules and buffers, which is needed before we can turn to the second type of knowledge in ACT-R, productions.

But as the very first thing, we have to import the relevant package:

```
[py2] >>> import pyactr as actr                                    1
```

We use the `as` keyword, so that every time we use the `pyactr` package, we can write `actr` instead of the longer `pyactr`.

2.5 Writing chunks in `pyactr`

There is one thing we have to do before writing chunks themselves: we should start by specifying a chunk type and all the slots you think it should have. This will help you be clear about your intentions on what should be carried in declarative memory from the start. Let's create a chunk type that will correspond to our knowledge of words, as indicated above.

Needless to say, we don't strive here for the linguistically realistic theory of word representations at this point. It is just a toy example, showing the inner workings of ACT-R. Anyway, here is our chunk type:

```
[py3] >>> actr.chunktype("word", "phonology, meaning, category, number")
```

The function `chunktype` creates a type `word`, which consists of the following slots: `phonology`, `meaning`, `category`, `number`. The type itself is written as the first argument of the function, the slots are written as the second argument and are separated by commas.

After declaring the chunk type, we can create new chunks using this type.

```
[py4] >>> car = actr.makechunk(nameofchunk="car",\
      ...                      typename="word",\
      ...                      phonology="/ka:/",\
      ...                      meaning="[[car]]",\
      ...                      category="noun",\
      ...                      number="sg")
      >>> print(car)
      word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/)
```

The chunk is created using the function `makechunk`. Every `makechunk` has two fixed arguments: `nameofchunk` ([**py4**], line 1), `typename` ([**py4**], line 2). Furthermore, it has slot-value pairs, present in the chunk. Lines 3-6 show how values of slots are specified. You do not have to specify all the slots that a chunk of a particular type should have (in that case, the particular slots are empty). We finally print the chunk (line 7). Notice that the order of slot-value pairs is different than in instantiating the chunk (i.e., we defined `phonology` as first, but it appears as the last in the output). This is because chunks are unordered lists of slot-value pairs. Python assumes some arbitrary (alphabetic) ordering when printing chunks.

Specifying chunk types is optional. In fact, the information about chunk type is relevant for `pyactr`, but it has no theoretical significance (it's just a syntactic sugar). However, it is recommended, as doing so might clarify what kind of attribute-value matrices you will need in your model. Also if you don't specify the chunk type that your chunk uses, Python prints a warning message. This might help you debug your code (e.g., if you accidentally named your chunk "morphreme", you would get a warning message that a new chunk type has been created – probably, not what you wanted; warnings are not displayed in book). (See Python documentation for more on warnings.)

It is also recommended that you only use attributes you defined first (or you used in the first chunk of a particular type). However, you can always add new attributes along the way (it is assumed that other chunks up to now had no value for those attributes in that case). For example, imagine we realize that it's handy to specify what syntactic function a word is part of. We didn't have that in our example of car. So let's create a new chunk, `car2`, which is like `car` but it adds this extra piece of information (and we assume this word has been used as part of subject):

```
[py5] >>> car2 = actr.makechunk(nameofchunk="car2",\
      ...                      typename="word",\
      ...                      phonology="/ka:/",\
      ...                      meaning="[[car]]",\
```

```
... category="noun",\ 5
... number="sg",\ 6
... syncat="subject") 7
>>> print(car2) 8
word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/, syncat=subject) 9
```

Line 7 in [**py5**] is the new part. We are adding a new slot `syncat`, and assign it the value `subject`. The command goes through successfully (as shown by the fact that we can print `car2`), but a warning message is issued (not displayed above), namely "`UserWarning`: Chunk type word is extended with new attributes."

There is another way of specifying a chunk, which is maybe more intuitive: using `chunkstring`. In that case, you write down the chunk type after the `isa`-attribute, and attribute value pairs are written after each other, separated only by a comma.

[**py6**]
```
>>> car2 = actr.makechunk(nameofchunk="car2",\ 1
... typename="word",\ 2
... phonology="/ka:/",\ 3
... meaning="[[car]]",\ 4
... category="noun",\ 5
... number="sg",\ 6
... syncat="subject") 7
>>> print(car2) 8
word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/, syncat=subject) 9
```

We are using the new function `chunkstring`. It has the same power as `makechunk`. The argument `string` defines what the chunk consists of. The value pairs are written as a plain string. Notice that we use three quote marks, rather than one. These signal to Python that the string can appear on more than one line. The first slot-value pair ([**py6**], line 2) is special – it specifies the type of chunk, and a special slot is used for this, `isa`. Notice that the resulting chunk is identical to the previous one, as shown on [**py6**], line 8.

As we mentioned above, productions work by testing whether a particular condition is satisfied and then acting upon that. In practice, for most parts this means that productions check chunks. Thus, we have to define comparisons across chunks. This is done in an intuitive way: one chunk is identical to another if they have the same attributes and they have the same values for all the attributes. A chunk a is part of a chunk b if a has all the attributes of b and a has the same values as b in those attributes (however, chunk b might have extra attribute-value pairs).

`pyactr` overloads standard comparison operators for these tasks. The code below and its output should be self-explanatory:

[**py7**]
```
>>> car2 == car2 1
True 2
>>> car == car2 3
False 4
>>> car <= car2 5
True 6
>>> car < car2 7
True 8
>>> car2 < car 9
False 10
```

Note that chunk types are irrelevant for deciding part-of relations. This might be counter-intuitive, but that's just how ACT-R works – chunk types are 'syntactic sugar' useful only for the human modeler. This means that if we define a new chunk type that happens to have the same slots as another chunk type, one might be part of the other:

[**py8**]
```
>>> actr.chunktype("synlabel", "category")
>>> noun = actr.makechunk(nameofchunk="noun",
...                       typename="synlabel",
...                       category="noun")
>>> noun < car2
True
```

2.6 Modules and buffers

Chunks do not live in a vacuum, they are always part of an ACT-R architecture, which consists of modules and buffers. Each module in ACT-R serves a different task. Furthermore, modules cannot be accessed or updated directly in ACT-R; rather, this always happens through the use of a buffer, and each module comes equipped with one such buffer. A buffer, in its turn, is a carrier of exactly one chunk.

In this chapter, we will be concerned with only two modules, the goal module (representing one's goals) and the declarative module (representing one's declarative knowledge). These are the two most common modules in ACT-R. They appear with their buffers, which are called goal and retrieval, respectively.

For the sake of concreteness, let's create the declarative module and the goal and retrieval buffers. And since it does not make sense to think about modules without instantiating a model in which these modules work, let's start by doing just that:

[**py9**]
```
>>> agreement = actr.ACTRModel()
```

The command above instantiated an ACTRModel as the value of the variable `agreement`. We will now be filling in details of this model with information about buffers, models, and productions.

We start by creating relevant modules and buffers inside this model.

[**py10**]
```
>>> dm = agreement.DecMem()
>>> retrieval = agreement.dmBuffer(name="retrieval", declarative_memory=dm)
>>> g = agreement.goal(name="g")
```

- `DecMem` instantiates declarative memory. Notice that `DecMem` is an attribute of the model `agreement`. We just specified that this will be the declarative memory of our model and we bound it to the variable `dm`.

- `dmBuffer` instantiates the buffer of the declarative memory in the model. We fill in two arguments of this attribute. The second argument says to which declarative memory the buffer should be connected (i.e., from which memory it should be retrieving). The first argument says under what name the buffer will be seen in the model. The name of a buffer is needed if we are going to refer to these buffers later on in productions (without that productions would not be able to manipulate buffers). Notice also that

the variable we bind this buffer to has the same name as the name used in the model (`retrieval`). This is just convenience.

- `goal` instantiates the goal buffer.

The declarative memory was just instantiated, so it should be empty. Let's check that:

[**py11**]
```
>>> dm
{}
```

We might want to add the best chunk we created so far – `car2`:

[**py12**]
```
>>> dm.add(car2)
>>> print(dm)
{word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/, syncat=subject) {0.0}}
```

- Chunks are added by the attribute `add` on the declarative memory. As the argument, we specify a chunk (or chunks) that should be added.

`dm` now shows the chunk we added. It also ties the chunk to the time point at which it was introduced. Since we did not start any model simulation, the time point is 0 right now.

2.7 Writing productions in `pyactr`

In their core, productions are IF-statements.

Productions have two parts: left-hand side rules (tests) precede the double arrow (`==>`); right-hand side rules (actions) follow the arrow.

Let's now create productions that simulate a verb agreement.[1] We will simplify things a lot. We will only care about 3rd person agreement, present tense. We will do no syntactic parsing, just assume that our memory includes only the subject of the clause and we have the verb of the clause at our disposal. Since our goal is creating verb agreement, we should assume that the verb itself is all the time in the goal. What should agreement do? One production should state that IF goal has a verb and task is to agree THEN the subject should be retrieved. The second production should state that IF subject number in retrieval is `=x` THEN verb number in goal is `=x`. The third rule should say that if the verb is assigned a number the task is done.

Let's write down the second rule first.

[**py13**]
```
>>> agreement.productionstring(name="agree", string="""
...     =g>
...     isa verbagreement
...     task trigger_agreement
...     category 'verb'
...     =retrieval>
```

[1] The full code for this model is also available as `u1_agreement` on http://www.jakubdotlacil.com/tutorials and in the appendix to this chapter.

```
...     isa word                                                                                    7
...     category 'noun'                                                                             8
...     syncat 'subject'                                                                            9
...     number =x                                                                                   10
...     ==>                                                                                         11
...     =g>                                                                                         12
...     isa verbagreement                                                                           13
...     task done                                                                                   14
...     category 'verb'                                                                             15
...     number =x                                                                                   16
...     """)                                                                                        17
agree:                                                                                              18
{'=retrieval': word(category=noun, meaning=None, number=_variablesvalues(negvalues=None, negvari   19
==>                                                                                                 20
{'=g': verbagreement(category=verb, number=_variablesvalues(negvalues=None, negvariables=None, v   21
```

- Productions are created by the command `productionstring` and they have two arguments (later on, we will see that there is a third argument): `name` (the name of the production) and `string` (the string that specifies what the production does).

2.–11. The left hand side of the rule and the right hand side of the rule are separated by `==>`. That is, what appears before `==>` is tests, what appears after `==>` are actions. Second, tests and actions have always the same structure: first, you specify what buffer should be considered: this is done by writing the name of the buffer between `=` and `>` (see line 2 and 6). The name of the buffer has to match the name you used when you created these buffers. After choosing the buffer you specify a chunk (lines 3–5 and lines 7–10). In case of tests the chunks specified in a rule must be part of a chunk that is present in the corresponding buffer (i.e., the part-of test, discussed in Sect. writing-chunks-in-pyactr, must be true between the chunk specified in the test and the chunk in the corresponding buffer). Chunks in productions are written in the same way as chunks in the function `chunkstring`: you write slot-value pairs, and each slot and value are separated by one or more spaces. (We also wrote each pair on a separate line, but that is just aesthetics.) The `isa` slot is used to specify chunk types.

12.–17. If all tests are true, then a chunk in a buffer is modified as specified after ==>.

All in all, we can read the rule agree as follows: IF the goal buffer has a chunk with category verb and the task is to trigger agreemnt AND the retrieval buffer has a chunk with the category noun and syncat subject and it has some number, assigned to x, THEN modify the chunk in the goal buffer so that it carries the number that was assigned to x.

The other rule should appear as follows:

[**py14**]
```
>>> agreement.productionstring(name="retrieve", string="""                                          1
...     =g>                                                                                         2
...     isa verbagreement                                                                           3
...     task agree                                                                                  4
...     category 'verb'                                                                             5
...     ?retrieval>                                                                                 6
...     buffer empty                                                                                7
...     ==>                                                                                         8
```

```
...     =g>
...     isa verbagreement
...     task trigger_agreement
...     category 'verb'
...     +retrieval>
...     isa word
...     category 'noun'
...     syncat 'subject'
...     """)
agree:
{'=retrieval': word(category=noun, meaning=None, number=_variablesvalues(negvalues=None, negvari
==>
{'=g': verbagreement(category=verb, number=_variablesvalues(negvalues=None, negvariables=None, v
retrieve:
{'?retrieval': {'buffer': 'empty'}, '=g': verbagreement(category=verb, number=None, task=agree)}
==>
{'+retrieval': word(category=noun, meaning=None, number=None, phonology=None, syncat=subject), '
```

6. Instead of `=retrieval>` in the test, we write `?retrieval>`. While `=retrieval>` tests whether the retrieval carries a particular chunk `?retrieval>` queries the buffer directly. The query in this case checks whether the buffer is empty (i.e., it carries no chunk). Strictly speaking, this is not necessary (the model would work just as well without this test). But we add it here for instruction purposes.

13. We specify `+retrieval>` in actions. While `=retrieval>` would modify a chunk present in the buffer, `+` states that a new chunk should be created/set. In case of the retrieval buffer chunks are 'created' by being retrieved from their module of declarative memory (in our case, `dm`).

We will look at some more examples of querying in the next section (i.e., cases in which we use `?` instead of `=` in front of the name of a buffer). Before that, we add the third rule discussed above, which should check that the verb in goal carries a number, and if so, it should consider the task done.

[**py15**]
```
>>> agreement.productionstring(name="retrieve", string="""
...     =g>
...     isa verbagreement
...     task agree
...     category 'verb'
...     ?retrieval>
...     buffer empty
...     ==>
...     =g>
...     isa verbagreement
...     task trigger_agreement
...     category 'verb'
...     +retrieval>
...     isa word
...     category 'noun'
...     syncat 'subject'
...     """)
```

```
agree:
{'=retrieval': word(category=noun, meaning=None, number=_variablesvalues(negvalues=None, negvari
==>
{'=g': verbagreement(category=verb, number=_variablesvalues(negvalues=None, negvariables=None, v
retrieve:
{'?retrieval': {'buffer': 'empty'}, '=g': verbagreement(category=verb, number=None, task=agree)}
==>
{'+retrieval': word(category=noun, meaning=None, number=None, phonology=None, synset=subject),
```

8. \textasciitilde{}g\textgreater{} is an action we did not see before. It discards the chunk present in the goal buffer.

2.8 More examples on queries

So far, we mentioned only one way of querying - checking that a buffer is full. Here are some more cases:

[**py16**]
```
>>> '?g> buffer full'
'?g> buffer full'
>>> '?retrieval> state busy'
'?retrieval> state busy'
>>> '?retrieval> state error'
'?retrieval> state error'
```

- This checks whether a buffer is full (whether it carries a chunk).
- This is true if the retrieval buffer is working on retrieving a chunk.
- This is true if the last retrieval failed (no chunk has been found).

2.9 Running a model

We have almost everything ready to run our first model, we are just missing one piece: having a chunk in the goal buffer in the start of our simulation (without that, there is no goal and without a goal, the model has no reason to change its internal state). So let's add the goal:

[**py17**]
```
>>> actr.chunktype("verbagreement", "task, category")
>>> g.add(actr.chunkstring(string="isa verbagreement task agree category 'verb'"))
>>> g
{verbagreement(category=verb, task=agree)}
```

- The chunk is added to the goal buffer in the same way as to other modules and buffers – by the attribute `add`.

We can now run the model.

[**py18**]
```
>>> simulation = agreement.simulation()
>>> simulation.run()
(0, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0, 'PROCEDURAL', 'RULE SELECTED: retrieve')
(0.05, 'PROCEDURAL', 'RULE FIRED: retrieve')
(0.05, 'g', 'MODIFIED')
(0.05, 'retrieval', 'START RETRIEVAL')
(0.05, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.05, 'PROCEDURAL', 'NO RULE FOUND')
(0.1, 'retrieval', 'CLEARED')
(0.1, 'retrieval', 'RETRIEVED: word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/,
(0.1, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.1, 'PROCEDURAL', 'RULE SELECTED: agree')
(0.15, 'PROCEDURAL', 'RULE FIRED: agree')
(0.15, 'g', 'MODIFIED')
(0.15, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.15, 'PROCEDURAL', 'NO RULE FOUND')
```

- First, we have to instantiate the simulation of the model.
- The simulation is run.

What you see in the output is the trace of a model. Each line specifies three elements: the first element is time (in seconds), the second element is the module that is affected, the third element is a description of what's happening to the module.

The first line states that conflict resolution takes place in the module procedural (i.e., the module responsible for controlling production rules). This happens at time 0. There is one rule that matches the current state of affairs, and that is `retrieve` (`retrieve` requires that the goal buffer has a chunk with the category `verb` and an empty and free retrieval buffer). It can fire (i.e., its left-hand side is satisfied by the state of the model at 0 ms, so we can proceed to the right-hand side of the production rule). In ACT-R, firing takes 50 ms, as we see above in the time specification of the third line. After that, goal is (vacuously) modified (the modification is vacuous given our rules above). Then the retrieval starts, and it takes 50 ms to finish the retrieval. When the retrieval happens (line 9), the retrieval buffer carries the right chunk. Followingly, a new rule can be selected, `agree` (`agree` requires that the retrieval carries a subject chunk, and consequently, it modifies the chunk in goal to match the number between a verb and a boun.

After that, the last rule fires (`done`), which cleares the goal buffer. When the goal buffer is cleared, its information does not disappear. It is assumed in ACT-R that that information is transferred to the declarative memory. This is also the case here (our past goals become our newly acquired memory facts).

We can now check the final state of the declarative memory to see that this is the case:

[**py19**]
```
>>> dm
{word(category=noun, meaning=[[car]], number=sg, phonology=/ka:/, syncat=subject): {0.0}}
```

2.10 Example 2 – a top-down parser

We will now turn to a more realistic case, a parser. There will be more parsers considered throughout the tutorials. Our starting point is one of the simplest parsers – a top-down parser.[2]

Suppose we have a context-free grammar with the following rules:

S → NP VP
NP → ProperN
VP → V NP

Furthermore, there are two nouns and one verb in our language: Mary, Bill, likes. We will analyze one sentence with our parser, Mary likes Bill.

A top-down parser can be understood as a push-down automaton. Push-down automata have a memory, represented as a stack. In the parser, the stack represents categories that have to be parsed. For example, the stack may consist of one symbol, S - this would express that a sentence needs to be parsed (obviously, this is the starting point of a parser). Or the stack could consist of two elements: NP, VP – expressing that the parser needs to parse an NP, followed by parsing a VP.

The parser proceeds by modifying the contents of its stack based on two pieces of information: the top element on its stack (also written as the leftmost element below) and, possibly, a word that has to be parsed (the leftmost word in the stream of words).

We can sum up the parsing rules into just two general algorithm schemata (see, for example, Hale 2014):

- expand: if the stack shows a symbol X on top, and the grammar contains a rule X -> A B or X -> A, replace the symbol X with the symbol A, B or the symbol A, respectively.
- scan: if the stack shows a terminal and w, the word to be parsed, is of the right category, then remove the terminal from the stack and w from the parsed sentence.

We will now implement these general parsing rules to our grammar, which will be able to parse the sentence Mary likes Bill.

2.10.1 First steps in the model

Let us start with the first standard step, importing `pyactr`.

[**py20**]
```
>>> import pyactr as actr
```
1

Now, we should specify what chunktypes we need. We will have one chunktype for the parser. This will keep the information about stack contents, what word was parsed but also what the current task of the parser is (for most parts, it will be just that, parsing).

[**py21**]
```
>>> actr.chunktype("parsing", "task stack_top stack_bottom parsed_word ")
```
1

[2] The full code for this model is also available as u1_topdownparser on: http://www.jakubdotlacil.com/tutorials

- The chunk type has four slots: what task we are doing, what the current top element in the stack is, what the bottom element is and what the parsed word is. Note that we have only two positions in our chunktype, stack top and stack bottom. This suffices for the simple case of binary structures we consider here, so we will leave it at this.

The second chunktype will represent the sentence. This might look weird: why should we represent a sentence in a chunk? In most of the cases, the sentence is external to an agent, it's what the agent reads or hears. However, at this point we have no way to represent the surrounding environment, so we have to represent a sentence internally, as a chunk. Later on, we will see a more elegant solution. The chunktype sentence will be assumed to carry at most three words.

[**py22**]
```
>>> actr.chunktype("sentence", "word1 word2 word3")
```

We will now initialize the model and assume it has a declarative memory, retrieval and a goal buffer.

[**py23**]
```
>>> parser = actr.ACTRModel()
>>> dm = parser.DecMem()
>>> retrieval = parser.dmBuffer(name="retrieval", declarative_memory=dm)
>>> g = parser.goal(name="g")
```

- We call our model `parser`.
- The declarative memory is declared in the standard way, using the attribute `DecMem`.
- The retrieval is declared in the standard way. We tie it to the just created declarative memory.
- `g` is our goal buffer.

The goal buffer will carry the information about parsing (that is, it will have the chunk `parsing`, whose type was already created). But we also need to carry the information about the parsed sentence (the chunk `sentence`). It would be nice to leave that information to the environment but we cannot do it yet, so let's create a second buffer, which is identical to goal and which carries the information about a sentence. In fact, that is not such a strange solution. ACT-R commonly assumes two goal buffers, one, which we used so far and which keeps information about one's goals, another one which keeps the internal image of current information. It might not be so far-fetched to use the imaginal buffer for the sentence itself. We will start this new buffer.

[**py24**]
```
>>> g2 = parser.goal(name="g2", set_delay=0.2)
```

- The imaginal buffer, `g2`, is created in almost the same way as the goal buffer. However, one extra argument is specified: `set\_delay`. This parameter specifies the delay required to set a chunk in the buffer. That is, it would take 0.2 s to set a chunk in g2. This is the standard value for the imaginal buffer (the goal buffer requires only 0.05 s to set a chunk).

We can now add chunks into g and g2.

[**py25**]
```
>>> g.add(actr.chunkstring(string="isa parsing  task parse stack_top 'S'"))
>>> g2.add(actr.chunkstring(string="isa sentence word1 'Mary' word2 'likes' word3 'Bill'"))
```

- We assume that the parser's goal is to parse a sentence.
- The sentence to be parses is *Mary likes Bill*.

The toughest part is coming now: how to code the parsing itself?

We will assume that grammar (and parsing rules stemming from grammar) is part of production knowledge. This is in contrast to lexical information, which is commonly treated as part of declarative memory (see Lewis and Vasishth 2005, for arguments for this distinction). So, our first task is to specify lexical knowledge. Let's do that (only syntactic categories will be specified):

[**py26**]
```
>>> actr.chunktype("word", "form, cat")
>>> dm.add(actr.chunkstring(string="isa word form 'Mary' cat 'ProperN'"))
>>> dm.add(actr.chunkstring(string="isa word form 'Bill' cat 'ProperN'"))
>>> dm.add(actr.chunkstring(string="isa word form 'likes' cat 'V'"))
```

- We start by creating a new type that will accommodate lexical information.

2.–4. We have three words. Their values should be obvious.

We now have to specify production rules that mimic context-free grammar rules and that encode top-down parsing, represented in the schemata expand and scan.

2.10.2 Production rules

Let's start with the first rule, expanding S into NP and VP. This should be relatively straightforward. We specify it as:

[**py27**]
```
>>> parser.productionstring(name="expand: S->NP VP", string="""
...     =g>
...     isa  parsing
...     task parse
...     stack_top 'S'
...     ==>
...     =g>
...     isa parsing
...     stack_top 'NP'
...     stack_bottom 'VP'
... """)
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
```

2. The rule tests against the goal buffer.

3.–5. It requires that the goal buffer carries a chunk whose task is to parse and whose element on top is S.

7. Its action is to modify the goal buffer.

8.–10. The rule will set the top element as NP and the bottom as VP. That is, this is the rule that expands S into NP and VP according to the abstract schema discussed above (see the general algorithm schema expand).

Notice that this oversimplifies things slightly. If we now have a symbol following S in the stack, it would be overwritten by VP - hardly a behavior we would want to have. This oversimplification is to a large extent caused by the fact that we only work with two-element stack. It will not affect our example or several other examples, so we will leave this simplification in place.

The second rule states that NP is expanded into ProperN:

[**py28**]
```
>>> parser.productionstring(name="expand: NP->ProperN", string="""
...     =g>
...     isa parsing
...     task parse
...     stack_top 'NP'
...     ==>
...     =g>
...     isa parsing
...     stack_top 'ProperN'
... """)
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

9. The rule says that the symbol on the top of the stack should be rewritten from NP to N. Notice that unlike the previous rule, nothing is done to the bottom of the stack. Thus, it will be left unmodified.

The third rule in our grammar describes the expansion of VP into V and NP. So let's deal with it in the parallel way as the previous rules:

[**py29**]
```
>>> parser.productionstring(name="expand: VP -> V NP", string="""
...     =g>
...     isa parsing
...     task parse
...     stack_top 'VP'
...     ==>
...     =g>
...     isa parsing
```

```
...     stack_top 'V'
...     stack_bottom 'NP'
... """)
expand: VP -> V NP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

1.–10. Notice that the rule is almost identical to the first rule. We only changed the symbols, according to the context-free grammar rules.

Now, for the most complext part. Once we have terminals (ProperN, V), we have to check that the terminal matches the category of the word to be parsed. If so, the word is scanned.

We achieve this by splitting the task into two rules. If we have a terminal, say ProperN, the category of the word has to be retrieved from memory (rule `retrieve`). If the category matches the top of stack, the word is scanned.

[**py30**]
```
>>> parser.productionstring(name="retrieve: ProperN", string="""
...     =g>
...     isa parsing
...     task parse
...     stack_top 'ProperN'
...     =g2>
...     isa sentence
...     word1 =w1
...     ==>
...     =g>
...     isa parsing
...     task retrieving
...     +retrieval>
...     isa word
...     form =w1
... """)
retrieve: ProperN:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
expand: VP -> V NP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
```

```
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

2.–5. We test that the top of the stack has a terminal, ProperN.

6.–8. The imaginal buffer has the leftmost word; the word is assigned to the variable w1.

10.-12. The goal is switched from parsing to retrieving.

13.–15. The retrieval starts. We are retrieving the chunk with the form of w1. This will retrieve a chunk with the lexical information about the particular word.

[**py31**]
```
>>> parser.productionstring(name="retrieve: V", string="""
...     =g>
...     isa parsing
...     task parse
...     stack_top 'V'
...     =g2>
...     isa sentence
...     word1 =w1
...     ==>
...     =g>
...     isa parsing
...     task retrieving
...     +retrieval>
...     isa word
...     form =w1
... """)
retrieve: ProperN:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
expand: VP -> V NP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
retrieve: V:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

5. We test that the top of the stack has a terminal, V. APart from this one line, the rule is identical to the previous one.

Now, we define the rule that deals with the retrieved information and scans the upcoming word:

```
[py32] >>> parser.productionstring(name="scan: string", string="""
       ...     =g>
       ...     isa parsing
       ...     task retrieving
       ...     stack_top =y
       ...     stack_bottom =x
       ...     =retrieval>
       ...     isa word
       ...     form =w1
       ...     cat =y
       ...     =g2>
       ...     isa sentence
       ...     word1 =w1
       ...     word2 =w2
       ...     word3 =w3
       ...     ==>
       ...     =g>
       ...     isa parsing
       ...     task print
       ...     stack_top =x
       ...     stack_bottom empty
       ...     parsed_word =w1
       ...     =g2>
       ...     isa sentence
       ...     word1 =w2
       ...     word2 =w3
       ...     word3 empty
       ... """)
       expand: S->NP VP:
       {'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
       ==>
       {'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
       expand: VP -> V NP:
       {'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
       ==>
       {'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
       retrieve: ProperN:
       {'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
       ==>
       {'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
       retrieve: V:
       {'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
       ==>
       {'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
       scan: string:
       {'=retrieval': word(cat=_variablesvalues(negvalues=None, negvariables=None, values=None, variabl
```

```
==>
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

2.–6. This checks that the goal buffer has the task `retrieving`. Furthermore, it assigns stack symbols to two variables.

7.–10. The syntactic category of the retrieval must match the symbol on top of the stack.

11.–15. The imaginal buffer carries the sentence. Three words are assigned to three variables.

17.–22. This action achieves that the symbol on the bottom of the stack is moved to the top position. Notice also that the goal buffer has been changed into a new stage, print. This is not necessary, it serves only the purpose of checking that everything went fine. We want to print the word that has been currently parsed. We will do that in a separate production. For the same reason, we keep the information about the currently parsed word in the goal buffer, in the slot parsed_word.

23.–27. Words are moved one level up (the word on the second position is moved to the first position etc.). The last position is left empty.

The printing production that follows scanning the string, is specified below:

[**py33**]
```
>>> parser.productionstring(name="print parsed word", string="""
...     =g>
...     isa parsing
...     task print
...     =g2>
...     isa sentence
...     word1 ~empty
...     ==>
...     !g>
...     show parsed_word
...     =g>
...     isa parsing
...     task parse
...     parsed_word None""")
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
print parsed word:
{'=g2': sentence(word1=_variablesvalues(negvalues=empty, negvariables=None, values=None, variabl
==>
{'!g': (['show', 'parsed_word'], {}), '=g': parsing(parsed_word=_variablesvalues(negvalues=None,
expand: VP -> V NP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
==>
```

```
{'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
retrieve: ProperN:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
retrieve: V:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
scan: string:
{'=retrieval': word(cat=_variablesvalues(negvalues=None, negvariables=None, values=None, variabl
==>
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

2.–4. This tests that the goal buffer has the task `print`.

5.–7. The value of the slot `word1` in the imaginal buffer is not empty (the squiggle is negation).

9.–10. -

11.–12. This part will print the parsed word. !g> says that Python should carry out an action in the goal buffer. After !g>, we have to specify what Python should do: we specify that we want Python to show something (i.e., it should execute the method `show`) and what should be shown, that is, the value of the slot `parsed\_word`.

13.–16. The last action deletes whatever was in `parsed\_word`.

The last production we have to consider is the production at the end of parsing. The parsing ends when `word1` has the value empty and the task is `print` (i.e., no parsing or retrieving is going on in the goal buffer). As a way of summary, we will also print all our rules.

[**py34**]
```
>>> productions = parser.productionstring(name="done", string="""
...     =g>
...     isa parsing
...     task print
...     =g2>
...     isa sentence
...     word1 empty
...     ==>
...     =g>
...     isa parsing
...     task done
...     !g>
...     show parsed_word
...     ~g2>
...     ~g>""")
>>> print(productions)
done:
```

```
{'=g2': sentence(word1=empty, word2=None, word3=None), '=g': parsing(parsed_word=None, stack_bot
==>
{'~g2': None, '!g': (['show', 'parsed_word'], {}), '~g': None, '=g': parsing(parsed_word=None, s
expand: S->NP VP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=S, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=VP, stack_top=NP, task=None)}
print parsed word:
{'=g2': sentence(word1=_variablesvalues(negvalues=empty, negvariables=None, values=None, variabl
==>
{'!g': (['show', 'parsed_word'], {}), '=g': parsing(parsed_word=_variablesvalues(negvalues=None,
expand: VP -> V NP:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=VP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=NP, stack_top=V, task=None)}
retrieve: ProperN:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
retrieve: V:
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
==>
{'+retrieval': word(cat=None, form=_variablesvalues(negvalues=None, negvariables=None, values=No
scan: string:
{'=retrieval': word(cat=_variablesvalues(negvalues=None, negvariables=None, values=None, variabl
==>
{'=g2': sentence(word1=_variablesvalues(negvalues=None, negvariables=None, values=None, variable
expand: NP->ProperN:
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=NP, task=parse)}
==>
{'=g': parsing(parsed_word=None, stack_bottom=None, stack_top=ProperN, task=None)}
```

1. We bind the output to the variable `productions`. The output is all the production rules in the model. We can print them afterwards.

6.–8. We check that there is no leftmost word (the whole sentence was parsed).

14.–15. The imaginal and goal buffers are cleared.

16. We print all production rules.

2.10.3 Running the model

We run the model in the same way as before.

[**py35**]
```
>>> sim = parser.simulation()
>>> sim.run()
(0, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0, 'PROCEDURAL', 'RULE SELECTED: expand: S->NP VP')
(0.05, 'PROCEDURAL', 'RULE FIRED: expand: S->NP VP')
(0.05, 'g', 'MODIFIED')
(0.05, 'PROCEDURAL', 'CONFLICT RESOLUTION')
```

```
(0.05, 'PROCEDURAL', 'RULE SELECTED: expand: NP->ProperN')
(0.1, 'PROCEDURAL', 'RULE FIRED: expand: NP->ProperN')
(0.1, 'g', 'MODIFIED')
(0.1, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.1, 'PROCEDURAL', 'RULE SELECTED: retrieve: ProperN')
(0.15, 'PROCEDURAL', 'RULE FIRED: retrieve: ProperN')
(0.15, 'g', 'MODIFIED')
(0.15, 'retrieval', 'START RETRIEVAL')
(0.15, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.15, 'PROCEDURAL', 'NO RULE FOUND')
(0.2, 'retrieval', 'CLEARED')
(0.2, 'retrieval', 'RETRIEVED: word(cat=ProperN, form=Mary)')
(0.2, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.2, 'PROCEDURAL', 'RULE SELECTED: scan: string')
(0.25, 'PROCEDURAL', 'RULE FIRED: scan: string')
(0.25, 'g2', 'MODIFIED')
(0.25, 'g', 'MODIFIED')
(0.25, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.25, 'PROCEDURAL', 'RULE SELECTED: print parsed word')
(0.3, 'PROCEDURAL', 'RULE FIRED: print parsed word')
Mary
(0.3, 'g', 'EXECUTED')
(0.3, 'g', 'MODIFIED')
(0.3, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.3, 'PROCEDURAL', 'RULE SELECTED: expand: VP -> V NP')
(0.35, 'PROCEDURAL', 'RULE FIRED: expand: VP -> V NP')
(0.35, 'g', 'MODIFIED')
(0.35, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.35, 'PROCEDURAL', 'RULE SELECTED: retrieve: V')
(0.4, 'PROCEDURAL', 'RULE FIRED: retrieve: V')
(0.4, 'g', 'MODIFIED')
(0.4, 'retrieval', 'START RETRIEVAL')
(0.4, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.4, 'PROCEDURAL', 'NO RULE FOUND')
(0.45, 'retrieval', 'CLEARED')
(0.45, 'retrieval', 'RETRIEVED: word(cat=V, form=likes)')
(0.45, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.45, 'PROCEDURAL', 'RULE SELECTED: scan: string')
(0.5, 'PROCEDURAL', 'RULE FIRED: scan: string')
(0.5, 'g2', 'MODIFIED')
(0.5, 'g', 'MODIFIED')
(0.5, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.5, 'PROCEDURAL', 'RULE SELECTED: print parsed word')
(0.55, 'PROCEDURAL', 'RULE FIRED: print parsed word')
likes
(0.55, 'g', 'EXECUTED')
(0.55, 'g', 'MODIFIED')
(0.55, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.55, 'PROCEDURAL', 'RULE SELECTED: expand: NP->ProperN')
(0.6, 'PROCEDURAL', 'RULE FIRED: expand: NP->ProperN')
(0.6, 'g', 'MODIFIED')
(0.6, 'PROCEDURAL', 'CONFLICT RESOLUTION')
```

```
(0.6, 'PROCEDURAL', 'RULE SELECTED: retrieve: ProperN')
(0.65, 'PROCEDURAL', 'RULE FIRED: retrieve: ProperN')
(0.65, 'g', 'MODIFIED')
(0.65, 'retrieval', 'START RETRIEVAL')
(0.65, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.65, 'PROCEDURAL', 'NO RULE FOUND')
(0.7, 'retrieval', 'CLEARED')
(0.7, 'retrieval', 'RETRIEVED: word(cat=ProperN, form=Bill)')
(0.7, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.7, 'PROCEDURAL', 'RULE SELECTED: scan: string')
(0.75, 'PROCEDURAL', 'RULE FIRED: scan: string')
(0.75, 'g2', 'MODIFIED')
(0.75, 'g', 'MODIFIED')
(0.75, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.75, 'PROCEDURAL', 'RULE SELECTED: done')
(0.8, 'PROCEDURAL', 'RULE FIRED: done')
Bill
(0.8, 'g', 'EXECUTED')
(0.8, 'g', 'MODIFIED')
(0.8, 'g2', 'CLEARED')
(0.8, 'g', 'CLEARED')
(0.8, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.8, 'PROCEDURAL', 'NO RULE FOUND')
```

- We instantiate the simulation of the model.
- The simulation is run.

This all looks good. We parsed the three words and we ended up in the stage done. We can also check our declarative memory. Since we cleared g and g2 at the end of done, it should consist of those elements (it should also carry the chunks we put in there before, the lexical knowledge). The chunks from `g` and `g2` should have empty positions in `stack\_top` and `stack\_bottom`, as well as `word1` – `word3`. Let's see.

[**py36**]
```
>>> dm
{word(cat=ProperN, form=Bill): {0.0}, sentence(word1=empty, word2=empty, word3=empty): {0.8}, wo
```

This is all good.

As a further check, let's see whether our simple parser correctly fails if we feed it an ungrammatical sentence, say *Bill Mary likes*. It should fail during parsing of the second word, *Mary*, because the noun would not match its expectations.

We add relevant chunks into the goal and the imaginal buffers and start the new simulation.

[**py37**]
```
>>> g.add(actr.chunkstring(string="isa parsing  task parse stack_top 'S'"))
>>> g2.add(actr.chunkstring(string="isa sentence word1 'Bill' word2 'Mary' word3 'likes'"))
>>> sim = parser.simulation()
>>> sim.run()
(0, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0, 'PROCEDURAL', 'RULE SELECTED: expand: S->NP VP')
```

```
(0.05, 'PROCEDURAL', 'RULE FIRED: expand: S->NP VP')
(0.05, 'g', 'MODIFIED')
(0.05, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.05, 'PROCEDURAL', 'RULE SELECTED: expand: NP->ProperN')
(0.1, 'PROCEDURAL', 'RULE FIRED: expand: NP->ProperN')
(0.1, 'g', 'MODIFIED')
(0.1, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.1, 'PROCEDURAL', 'RULE SELECTED: retrieve: ProperN')
(0.15, 'PROCEDURAL', 'RULE FIRED: retrieve: ProperN')
(0.15, 'g', 'MODIFIED')
(0.15, 'retrieval', 'START RETRIEVAL')
(0.15, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.15, 'PROCEDURAL', 'RULE SELECTED: scan: string')
(0.2, 'retrieval', 'CLEARED')
(0.2, 'PROCEDURAL', 'RULE FIRED: scan: string')
(0.2, 'retrieval', 'RETRIEVED: word(cat=ProperN, form=Bill)')
(0.2, 'g2', 'MODIFIED')
(0.2, 'g', 'MODIFIED')
(0.2, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.2, 'PROCEDURAL', 'RULE SELECTED: print parsed word')
(0.25, 'PROCEDURAL', 'RULE FIRED: print parsed word')
Bill
(0.25, 'g', 'EXECUTED')
(0.25, 'g', 'MODIFIED')
(0.25, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.25, 'PROCEDURAL', 'RULE SELECTED: expand: VP -> V NP')
(0.3, 'PROCEDURAL', 'RULE FIRED: expand: VP -> V NP')
(0.3, 'g', 'MODIFIED')
(0.3, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.3, 'PROCEDURAL', 'RULE SELECTED: retrieve: V')
(0.35, 'PROCEDURAL', 'RULE FIRED: retrieve: V')
(0.35, 'g', 'MODIFIED')
(0.35, 'retrieval', 'START RETRIEVAL')
(0.35, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.35, 'PROCEDURAL', 'NO RULE FOUND')
(0.4, 'retrieval', 'CLEARED')
(0.4, 'retrieval', 'RETRIEVED: word(cat=ProperN, form=Mary)')
(0.4, 'PROCEDURAL', 'CONFLICT RESOLUTION')
(0.4, 'PROCEDURAL', 'NO RULE FOUND')
```

- The goal should be to parse a sentence, as before.
- The imaginal buffer should carry the information about the sentence, *Bill Mary likes*.

This is good. The parser correctly parsed the first word, but it failed at the second word. After it was retrieved, the parser could not match its category to the top of the stack (which required V).

But it is not enough that the parser correctly parses grammatical sentences and fails in ungrammatical ones. ACT-R is not a theory of computationally effective parsers, it is a theory of human cognition. ACT-R parsers should then model human processing as realistically as possible. Is that so in this case? One thing we would expect from such a parser is that its

time requirements should correspond to human processing. We see that it takes 800 ms to parse the sentence *Mary likes Bill*. This might be roughly correct, but there are things to worry about. For example, the parser requires this much time while abstracting away from what people have to do during parsing (internalizing visual information, projecting sentence meaning, a.o.), so ultimately, 800 ms might be too much given the amount of work this parser does. Another worry is that retrieving lexical information always takes 50 ms (see above). But this is hardly realistic. We know that lexical retrieval is dependent on various factors, and frequency is probably the most relevant one. This is completely ignored here. Finally, top-down parsers works quite well for a right-branching structures like the sentence *Mary likes Bill*, but it would have problems with left branching. In left branching the parser would have to store as many symbols on the stack as there are levels of embedding. Since every expansion of a rule takes 50 ms, we would expect that left branching structures of n-level embeddings should take $50 * n$ ms. This is at odds with human perforamce (cf. Resnik 1992). Thus, there is a lot of room for improvement to get to a more plausible human parser.

2.10.4 Stepping through a model

So far, when we checked a model, we always did that in one step, by running it from start to the end. This is fine, but there are cases when we might want to proceed more carefully. For example, we might want to check each step to see at which point the goal buffer gets its `parsed\_word`. Or our model is running an infinite loop, and we only want to check what's going on in the first few rules. Or we want to check what our declarative memory looks like after the retrieval is cleared for the first time. Etc.

For all these cases, it is handy to step through the simulation, rather than running it as a whole. Let's start our model again and do that.

[**py38**]
```
>>> g = parser.goal(name="g")
>>> g2 = parser.goal(name="g2", set_delay=0.2)
>>> g.add(actr.chunkstring(string="isa parsing  task parse stack_top 'S'"))
>>> g2.add(actr.chunkstring(string="isa sentence word1 'Bill' word2 'likes' word3 'Mary'"))
>>> sim = parser.simulation()
>>> sim.step()
```

Ok, what's that? Nothing happened so far. The simulation only proceeded through the first step (setting up the model), and there is no output. Let's add some more steps:

[**py39**]
```
>>> for _ in range(10):
...     sim.step()
```

- We add more steps using the for-loop. This line says that the loop will run 10 times.
- Every time, the simulation steps forward by one step.

Ok, now we proceeded through 10 steps and got some meagre output. (There are steps in the simulation that do not yield any output – mainly, setting up the model, but some other steps, too.)

Let's now move to the point at which the rule 'scan: string' has just fired.

In order to be able to do that, we have to be able to see into the current event. The current event is the attribute of the model. This is how we can check it:

[py40]
```
... parser.current_event
  File "<stdin>", line 3
    parser.current_event
         ^
SyntaxError: invalid syntax
```

The event has three arguments: time, proc and action. Time is the time at which the event took place. proc is the name of the module that's affected. action represents the action that's taking place. So, let's move to the action of firing of 'scan: string'.

[py41]
```
>>> while parser.current_event.action != 'RULE FIRED: scan: string':
...     sim.step()
```

- We specify a loop that will run until the action is 'scan: string'.
- The simulation proceeds forward while the loop is True.

Now, we can check, for example, what our buffers look like:

[py42]
```
... g
  File "<stdin>", line 3
    g
    ^
SyntaxError: invalid syntax
>>> g2
{sentence(word1=Bill, word2=likes, word3=Mary)}
```

2.11 Exercise

As an exercise, consider expanding the top-down parser. Additionally to what we have now, we should also be able to process the following rules from our grammar:

VP → V CP
VP → V
CP → C S

Furthermore, we will add following lexical items into our memory: that, cat C; believes, cat V; sleeps, cat V; John, cat ProperN.

With these additions, you should be able to parse sentences like 'Mary believes that Bill sleeps' (but see below).

You can probably see right away that the created parser might run into problems. For example, the parser might get stuck if you feed it the sentence 'Mary believes that Bill likes Mary' and it decides to expand the first VP into V and NP or into just V. This is a typical property of top-down parsers: they hypothesize about categories/structures before seeing them. In our model, the parser will have several ways to expand VP, so it should run into troubles when it uses the rule that happens to be incompatible with input.

So, what happens in those cases? What will our ACT-R top down parser do? What do you think?

The problem with top-down parsing can be avoided if we switch our strategy: rather than postulating the structure before having evidence, we might want to defer creating the

structure until all the relevant evidence is available. This different strategy has a name - it is a bottom-up parser. We will consider how it can be built in ACT-R in the next chapter, as well as some other models relevant for language.

Appendix: The agreement model

File **ch2_agreement.py**:

```
"""
An example of a very simple model that simulates subject-verb agreement. We abstract away from syntac
"""

import pyactr as actr

car = actr.makechunk(nameofchunk="car",\
                     typename="word", phonology="/ka:/", meaning="[[car]]", category="noun", number=

agreement = actr.ACTRModel()

dm = agreement.DecMem()
dm.add(car)

retrieval = agreement.dmBuffer(name="retrieval", declarative_memory=dm)

g = agreement.goal(name="g")
g.add(actr.chunkstring(string="isa word task agree category 'verb'"))

agreement.productionstring(name="agree", string="""
    =g>
    isa  word
    task trigger_agreement
    category 'verb'
    =retrieval>
    isa  word
    category 'noun'
    syncat 'subject'
    number =x
    ==>
    =g>
    isa  word
    task done
    category 'verb'
    number =x
    """)

agreement.productionstring(name="retrieve", string="""
    =g>
    isa  word
    task agree
    category 'verb'
    ?retrieval>
    buffer empty
    ==>
    =g>
    isa  word
    task trigger_agreement
```

```
    category 'verb'
    +retrieval>
    isa  word
    category 'noun'
    syncat 'subject'
    """)

agreement.productionstring(name="done", string="""
    =g>
    isa  word
    task done
    category 'verb'
    number =x
    ==>
    ~g>""")

if __name__ == "__main__":
    x = agreement.simulation()
    x.run()
```

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