Part VII: Semantic Memory

Semantic memory (SMem) in Soar is a mechanism that allows agents to deliberately store and retrieve objects that are persistent. This information supplements what is contained in short-term working memory and other long-term memories, such as rules in procedural memory.

1. The Semantic Store

Before we delve into how an agent can use semantic memory, let's see an example of preloading knowledge and viewing the contents of the memory.

First, open the Soar Debugger. Then, execute the following command (this can be loaded from a source file just as any other Soar command):

```
smem --add {
       (<a> ^name alice ^friend <b>)
       (<b> ^name bob ^friend <a>)
       (<c> ^name charley)
}
```

As we shall see in a moment, executing this command adds three objects to semantic memory. In general, the *smem --add* command is useful to preload the contents of large knowledge bases in Soar.

We can view the contents of semantic memory using the following command:

```
print @
```

Which will output the following result:

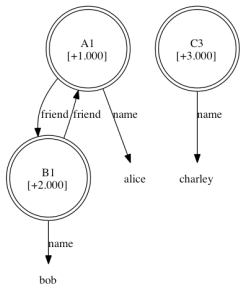
```
(@1 ^friend @2 ^name alice [+0.000])
(@2 ^friend @1 ^name bob [+0.000])
(@3 ^name charley [+0.000])
```

Note first that the variables from the *smem --add* command have been instantiated as specific identifiers (<a> as @1, <b> as @2, and <c> as @3). All identifiers in semantic memory are persistent, and thus we call them *long-term identifiers* (or LTIs), in contrast to all other identifiers, which are short-term. When printed, long-term identifiers are prefixed by the @ symbol and, when depicted, are shown using a double circle. The number in square brackets is the bias value of the object, used to break ties during retrievals, a topic to which we shall return later. Finally, unlike working memory and rules, the knowledge in semantic memory need not be connected, nor linked directly or indirectly, to a state.

To pictorially view the contents of semantic memory, we can use the visualize command to render the contents of semantic memory to an image. For example, execute the following command:

```
visualize smem
```

If you have graphviz and DOT installed (see http://graphviz.org for more detail), it should launch your system viewer to show a diagram similar to:



Now that we have seen the contents of semantic memory, you can confirm that none of this knowledge is present in any of the agent's other memories. For instance, execute the following commands to print the contents of working and procedural memories:

```
print --depth 100 <s>
print
```

You notice that the contents of the semantic store can be completely independent of the other memories, though, as discussed later, an agent can access and modify the store over time.

We are now done with this example and wish to clear the semantic store. To do this we issue a special command:

```
smem --clear
```

The agent is now reinitialized, as you can verify by printing the contents of working memory, procedural memory, and now semantic memory.

2. Agent Interaction

Agents interact with semantic memory via special structures in working memory. Soar automatically creates an *smem* link on each state, and each *smem* link has specialized substructure: a *command* link for agent-initiated actions and a *result* link for feedback from semantic memory. For instance, issue the following command:

```
print --depth 10 <s>
```

If you read the output carefully you will notice a WME that can be generally represented as (<state> ^smem <smem>) and two additional WMEs that can be represented as (<smem> ^command <cmd>) and (<smem> ^result <r>).

As described in the following sections, the agent, via rules, populates and maintains the *command* link and the architecture populates and cleans up the *result* link.

For the agent to interact with semantic memory, this mechanism must be enabled. By default, all learning mechanisms in Soar are disabled. To enable semantic memory, issue the following command:

```
smem --enable
```

3. Agent Storage and Modification

An agent stores an object to semantic memory by issuing a *store* command. The syntax of a store command is (<cmd> ^store <id>) where <cmd> is the *command* link of a state and <id> is an identifier.

An agent can issue multiple store commands simultaneously, and the commands are processed at the end of the phase in which they are issued. A *store* command is guaranteed to succeed and the response from the architecture will be a success WME: (<r> ^success <id>), where <r> is the *result* link of the state on which the *store* command was issued and <id> was the value of the *store* command.

A *store* command stores the identifier that is the result of the command, as well as any augmentations of that identifier. The command is not recursive. If the identifier to be stored was not long-term, it is changed in place to a long-term identifier. If it was already in semantic memory, the augmentations of the long-term identifier in semantic memory are overridden.

Let's see an example. Source the following rules into the Soar Debugger (they are available in the *smem-tutorial.soar* file within the *Agents* directory).

```
sp {propose*init
    (state <s> ^superstate nil
               -^name)
 -->
    (<s> ^operator <op> +)
    (<op> ^name init)}


 sp {apply*init
    (state <s> ^operator.name init
               ^smem.command <cmd>)
 -->
    (<s> ^name friends)
    (<cmd> ^store <a> <b> <c>)
    (<a> ^name alice ^friend <b>)
    (<b> ^name bob ^friend <a>)
```

```
    (<c> ^name charley)}

sp {propose*mod
   (state <s> ^name friends
              ^smem.command <cmd>)
   (<cmd> ^store <a> <b> <c>)
   (<a> ^name alice)
   (<b> ^name bob)
   (<c> ^name charley)

-->
   (<s> ^operator <op> +)
   (<op> ^name mod)}

 sp {apply*mod
    (state <s> ^operator.name mod
               ^smem.command <cmd>)
    (<cmd> ^store <a> <b> <c>)
    (<a> ^name alice)
    (<b> ^name bob)
    (<c> ^name charley)
 -->
    (<a> ^name alice -)
    (<a> ^name anna
         ^friend <c>)
    (<cmd> ^store <b> -)
    (<cmd> ^store <c> -)}
```

Now click the "Step" button to run till the decision phase and notice that the *init* operator is selected. Now, click the "Watch 5" button and then the "Run 1 -p" button to watch as the operator is applied. Below is part of the trace that should be produced. If you do not see this part of this trace in your run, be sure that you enabled semantic memory (see section above).

```
--- apply phase ---
--- Firing Productions (PE) For State At Depth 1 ---
Firing apply*init
+ (C3 ^name charley +  :O ) (apply*init)
+ (B1 ^friend A1 +  :O ) (apply*init)
+ (B1 ^name bob +  :O ) (apply*init)
+ (A1 ^friend B1 +  :O ) (apply*init)
+ (A1 ^name alice +  :O ) (apply*init)
+ (C2 ^store C3 +  :O ) (apply*init)
+ (C2 ^store B1 +  :O ) (apply*init)
+ (C2 ^store A1 +  :O ) (apply*init)
+ (S1 ^name friends +  :O ) (apply*init)
      --- Change Working Memory (PE) ---
=>WM: (25: C3 ^name charley)
=>WM: (24: B1 ^friend A1)
=>WM: (23: B1 ^name bob)
=>WM: (22: A1 ^friend B1)
=>WM: (21: A1 ^name alice)
=>WM: (20: C2 ^store A1)
=>WM: (19: C2 ^store B1)
=>WM: (18: C2 ^store C3)
```

```
=>WM: (17: S1 ^name friends)
```

Notice that the *apply*init* rule fired and added 3 *store* commands to working memory, where the identifiers to be stored are, initially, not long-term, and whose augmentations mirror the contents of the *smem --add* command in Part 1 of this tutorial. Then, at the end of the elaboration phase, semantic memory processed the command, converted the identifiers to long-term, and added status for each command.

Now, try printing the contents of semantic memory using the *print* @ command. You will see that semantic memory now has the same contents as after using the *smem --add* command in Part 1.

Application of the next operator modifies the contents of semantic memory by overriding the contents of an existing long-term identifier (@1). Click the "Step" button to select the next operator (*mod*) and then click the "Run 1 -p" button to apply the operator:

```
Firing apply*mod
- (A1 ^name alice +  :O ) (apply*init)
- (C2 ^store B1 +  :O ) (apply*init)
- (C2 ^store C3 +  :O ) (apply*init)
+ (A1 ^friend C3 +  :O ) (apply*mod)
+ (A1 ^name anna +  :O ) (apply*mod)
      --- Change Working Memory (PE) ---
=>WM: (33: A1 ^name anna)
=>WM: (32: A1 ^friend C3)
<=WM: (21: A1 ^name alice)
<=WM: (18: C2 ^store C3)
<=WM: (19: C2 ^store B1)
```

You will notice in the trace that the store commands for @2 and @3 are removed by the application rule, and that augmentations of @1 are removed and added. Then, at the end of the elaboration phase, semantic memory cleans up the status information for the old *store* commands.

Now, print the contents of semantic memory using the *print* @ command:

```
(@1 ^friend @2 @3 ^name anna [+1.000])
(@2 ^friend @1 ^name bob [+1.000])
(@3 ^name charley [+1.000])
```

Notice that the augmentations of @1 have indeed changed in semantic memory to reflect the new *store* command, while @2 and @3 remain unchanged.

4. Non-Cue-Based Retrieval

The first way an agent can retrieve knowledge from semantic memory is called a non-cue-based retrieval: the agent requests from semantic memory all of the augmentations of a known long-term identifier. The syntax of the command is (<cmd> ^retrieve <lti>) where <lti> is a short-term identifier that is linked to a long-

term identifier. In other words, it is a short-term identifier that was previously used in a store command or recalled via a retrieve or query command.

As an example, add the following three rules to our agent from Part 3 of this tutorial (these rules are already part of the *smem-tutorial.soar* file in the *Agents* directory):

```
sp {propose*ncb-retrieval
   (state <s> ^name friends
              ^smem.command <cmd>)
   (<cmd> ^store <a>)
   (<a> ^name anna
        ^friend <f>)
-->
   (<s> ^operator <op> + =)
   (<op> ^name ncb-retrieval
         ^friend <f>)}

sp {apply*ncb-retrieval*retrieve
   (state <s> ^operator <op>
              ^smem.command <cmd>)
   (<op> ^name ncb-retrieval
         ^friend <f>)
   (<cmd> ^store <a>)
-->
   (<cmd> ^store <a> -
          ^retrieve <f>)}

sp {apply*ncb-retrieval*clean
   (state <s> ^operator <op>
              ^smem.command <cmd>)
   (<op> ^name ncb-retrieval
         ^friend <f>)
   (<f> ^<attr> <val>)
-->
   (<f> ^<attr> <val> -)}
```

These rules retrieve all the information about one of @1's two friends (selected randomly) and remove the friend's augmentations (such as name and/or friend) from working memory.

Unlike *store* commands, all retrievals are processed during the agent's output phase and only one retrieval command can be issued per state per decision.

Now click the "Step" button and notice that one of the two *ncb* operators is selected. Click "Run 1 -p" to see the application rule create a *retrieve* command, requesting information about one of the two friends, as well as remove that friend's augmentations from working memory. Then click the "Run 1 -p" button again to proceed through the output phase. Finally, print the full contents of the *smem* link (*print --depth 10 L1*):

```
(L1 ^command C2 ^result R3)
(C2 ^depth 3 ^retrieve B1 (@2))
```

```
(R3 ^retrieved L2 (@2) ^success B1 (@2))
(L3 ^friend L2 (@2) ^friend L4 (@3) ^name anna)
(L2 ^friend L3 (@1) ^name bob)
(L4 ^name charley)
```

We see that semantic memory has retrieved and added to working memory the name of the friend, as well as indicated status for this command (*success*). Your run may have retrieved @3 instead, as a result of the random selection process:

Note that had the *retrieve* command been issued with an identifier that was not linked to a long-term identifier, the status would have been *failure* and there would be no *retrieved* structure. Note also that retrieved knowledge is limited to the augmentations of the long-term identifier: like the *store* command, the *retrieve* command is not recursive.

5. Cue-Based Retrieval

The second way an agent can retrieve knowledge from semantic memory is called a cue-based retrieval: the agent requests from semantic memory all of the augmentations of an unknown long-term identifier, which is described by a subset of its augmentations. The syntax of the command is (<cmd> ^query <cue>), where the desired augmentations all have <cue> as their identifier.

The augmentations of the cue form hard constraints, based upon the value of each WME. If the value of the WME is a constant (string, integer, or float) or long-term identifier, then any retrieval is required to have exactly the attribute/value pair specified. If the value of the WME is a short-term identifier, then any retrieval is required to have an augmentation that has the same attribute, but the value is unconstrained.

As an example, add the following two rules to our agent from Part 4 of this tutorial (these rules are already part of the *smem-tutorial.soar* file in the *Agents* directory):

```
sp {propose*cb-retrieval
   (state <s> ^name friends
              ^smem.command <cmd>)
   (<cmd> ^retrieve)
-->
   (<s> ^operator <op> + =)
   (<op> ^name cb-retrieval)}

sp {apply*cb-retrieval
   (state <s> ^operator <op>
              ^smem.command <cmd>)
   (<op> ^name cb-retrieval)
   (<cmd> ^retrieve <lti>)
-->
   (<cmd> ^retrieve <lti> -
          ^query <cue>)
   (<cue> ^name <any-name>
          ^friend <lti>)}
```

These rules retrieve an identifier that meets two constraints: (1) it has an augmentation where the attribute is “name”, but the value can be any symbol, and (2) it has an augmentation where the attribute is “friend” and the value is the long-term identifier retrieved as a result of applying the operator in Part 3.

As a reminder, all retrievals are processed during the agent’s output phase and only one retrieval command can be issued per state per decision.

So now click the “Step” button and then click the “Run 1 -p" to see the application rule create a *query* command, as well as remove the previous *retrieve* command from working memory. Then click the “Run 1 -p" button again to proceed through the output phase. Finally print the contents of the *smem* link (*print --depth 10 L1*):

```
(L1 ^command C2 ^result R3)
  (C2 ^depth 3 ^query C4)
    (C4 ^friend B1 (@2) ^name A2)
  (R3 ^retrieved L5 (@1) ^success C4)
    (L7 ^name charley)
    (L6 ^friend L5 (@1) ^name bob)
    (L5 ^friend L6 (@2) ^friend L7 (@3) ^name anna)
```

We see that semantic memory has retrieved and added to working memory the identifier @1 and all of its augmentations, as well as indicated status for this command (*success*). If in Part 4 of this tutorial your agent retrieved @3, you may have slightly different output.

Note that had no long-term identifier in semantic memory satisfied the constraints of the *query* command cue, the status would have been *failure* and there would be no retrieved structure. Note also that retrieved knowledge is limited to the augmentations of the long-term identifier: like the store command, retrievals are not recursive. We see this in the outputs above as one friend has augmentations (as a result of the *retrieve* command in Part 4), whereas the other does not.

If multiple identifiers had satisfied the constraints of the cue (such as if the cue had only a WME with “name” as the attribute and a short-term identifier as the value), then the long-term identifier with the largest bias value is returned. By default, the bias value is a monotonically increasing integer, reflecting the recency of the last storage or retrieval of an object.

It is also possible to *prohibit* one or more long-term identifiers from being retrieved. For more information on this any many additional capabilities of semantic memory, read the Semantic Memory chapter of the Soar Manual.