The Babel2 Manual

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Revision 3 (January 2011, final ALEAR version)

This document can be cited as:

AI-Memo 01-08, AI-Lab VUB, Brussels, Belgium, 2008.

@TECHREPORT { babel2manual,
    author = { Loetzsch, Martin and Wellens, Pieter and 
               De Beule, Joachim and Bleys, Joris and van Trijp, Remi },
    title = { The {B}abel2 Manual },
    number = { AI-Memo 01-08 },
    institution = { AI-Lab VUB },
    year = { 2008 },
    address = { Brussels, Belgium } }

This work was partially funded by the EU FET ECAgents Project IST-1940, by the FP7 ALEAR Project and by FWOAL328.
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1 Introduction

This document serves as a technical documentation of the Babel2 framework. It is work in progress and it is our aim to continuously improve and enhance the text. This manual accompanies Babel2 which can be downloaded for free at [http://arti.vub.ac.be/b2dl/](http://arti.vub.ac.be/b2dl/). Furthermore, [http://fcg-net.org](http://fcg-net.org) contains additional background information and downloadable papers that show in-depth experiments with Babel2.

Babel2 connects the implementations of our core technologies such as Fluid Construction Grammar (FCG) and Incremental Recruitment Language (IRL) with mechanisms for multi-agent interactions, robotic embodiment, cognitive processing and learning. An extensive monitoring system gives access to every detail of Babel2’s intermediate representations and dynamics and a high modularity ensures that the system can be used in a very wide variety of scenarios.

Babel2 is written in Common Lisp and runs in all major Lisp implementations on all major platforms. Its source code is frequently released to the public under the GNU General Public License.

1.1 Getting started

Please go to [http://arti.vub.ac.be/b2dl/](http://arti.vub.ac.be/b2dl/) and follow the instructions for setting up a Lisp environment, configuring Babel2 and testing the Babel2 installation.

1.2 Overview of Babel2

The file system structure of Babel2 consists of five important subdirectories:

- **systems** contains implementations of our core technologies:
  - **fcg**: Fluid Construction Grammar
  - **irl**: Incremental Recruitment Language
  - **experiment-framework**: for scripting of language games. Provides abstract classes such as `experiment`, `agent` and `world`. It also contains the base classes for learning. (see Chapter 4)
  - **tasks-and-processes**: A module that provides a way to organize and run multiple interdependent smaller tasks (called processes). It provides a basic best-first search to handle ambiguity when a process returns multiple options. (see Chapter 6)
  - **monitors**: a monitoring system for understanding the dynamics of experiments and obtaining scientific measurements (see Chapter 2)
web-interface: a web interface for visualizations.

utils: a collection of general utilities (see Chapter 3)

test-framework: unit tests for Babel2 components and experiments (Chapter 8)

libraries contains external libraries needed to run Babel2.

experiments contains the actual experiments. The reason to do them within Babel2 itself is the need for tight integration between the Babel2 core components and the experiments as well as the opportunity for sharing ideas and technological advancements between Babel2 users. Our actual experiments are not part of the Babel2 release.

sharing contains other technologies such as networks, construction dependencies, interfaces to robots or databases, specific learning operators, IRL primitives, etc. These building blocks complement the core technologies found in the systems folder when setting up experiments.

examples is a collection of didactic demonstrations and tutorials that illustrate how components of Babel2 can be used. We will list a few of them in the remainder of the Babel manual.
2 Utilities

The systems/utils/ folder contains a big variety of functions that were at some point considered useful in one or the other way (and many of them are frequently used). Here we will not list all of them but describe a few concepts found in the :utils system.

2.1 Copying Objects

Alternative hypothesis are processed in parallel. As for each alternative the agent’s state will deviate from the state at the branching point, a distinct copy of the relevant state is maintained for each branch. To facilitate custom, experiment specific implementations of parts of the state, a generic copy interface is provided which should be implemented for each new data type that represents some dynamic part of the agent’s state.

2.1.1 generic function copy-object

<table>
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<th>object</th>
<th>The thing to copy.</th>
</tr>
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<tr>
<td>default implementation</td>
<td>There are default implementations for atomic objects such as numbers and symbols that just return the value. Strings are copied with copy-seq. There is a default implementation for lists that calls copy-object on every element of the list and collects the results.</td>
</tr>
</tbody>
</table>

There is an implementation for (object t) that creates an instance of the class of object and calls copy-object-content to fill that new instance with the contents of object:

```lisp
(defmethod copy-object ((object t))
  (let ((copy (make-instance (class-of object))))
    (copy-object-content object copy) copy))
```

2.1.2 generic function copy-object-content

| source | destination |
description The function that is called by `copy-object` to do the work of copying the contents of `source` to `destination`. There are implementations for nearly all classes that are part of the FCG framework. If you add a new class and for example want to use that class as a part of a task, you will have to implement this method.

It is up to the developer to decide what is copied and what not. Normally it is assumed that `copy-object` returns a deep copy but this might often be less efficient.

`source` The object to copy.

`destination` The object to fill. Normally a newly created instance of the class of `source`.

example

```scheme
(defun copy-object-content ((source rule-set) (destination rule-set))
  (setf (slot-value destination 'type) (rule-set-type source))
  (setf (rules destination) (copy-list (rules source)))
  (setf (left-bins destination)
        (mapcar #'copy-seq (left-bins source)))
  (setf (right-bins destination)
        (mapcar #'copy-seq (right-bins source))))
```

method combination This generic function uses the custom method combination `call-all-applicable-methods`. When `copy-object-content` is called, not only the most specific applicable method but all applicable methods are called:

```scheme
(defun copy-object (object)
  (define-method-combination call-all-applicable-methods ()
    ((methods () :required t))
    'progn
      (loop for method in methods
            collect '(call-method ,method))))
```

This is very useful in such a case:

```scheme
(defun copy-object-content ((source A) (destination A))
  (print "copy slots of class A")
  (setf (a destination) (copy-object (a source))))

(defun copy-object-content ((source B) (destination B))
  (print "copy slots of class B")
  (setf (b destination) (copy-object (b source))))

(copy-object object)
```
The output is:
"copy slots of class A"
"copy slots of class B"

The standard method combination only would have called the `copy-object-content` method for class A (the first super class of C).

2.2 Blackboards

Cognitive processes in the Babel framework share their data using a blackboard architecture.

2.2.1 `structure blackboard`

description A “blackboard” is a set of “labeled” data “fields”. Such a field could be a rule set, an utterance, a meaning, etc.

slot `data-fields` (data-fields :type list :initform nil)

An association list consisting of (label . value) pairs.

copying blackboards Blackboards are copied by calling `copy-object` (see section 2.1.1) on every field value. So you have to make sure that the `copy-object-content` method is implemented for all the classes that you store in a blackboard.

2.2.2 `generic function fields blackboard`

description/ default Return a list containing the field labels of all fields of a blackboard.

implementation

blackboard A blackboard instance.

2.2.3 `generic function field? blackboard label`

description/ default Whether a field exists in blackboard. Returns two values. The first one returns t only when there is a field with the given label in the blackboard. The second one returns t if the first one is t and if there is a non-nil value attached to the field.

implementation

blackboard A blackboard instance.

label A symbol that labels the field.

2.2.4 `generic function add-data-field blackboard label initial-value`

description/ default Adds a data field to a blackboard. This has to be done explicitly before a field can be read or written. Additionally, you will get an error if the field is already present in the blackboard.

implementation
blackboard A blackboard instance.

label A symbol that labels the field.

initial-value A initial value for that field.

element (add-data-field *my-task* 'topic nil)

2.2.5 generic function get-data blackboard label
description/ default Returns the value of a data field for a given label. Throws an error if the field does not exist.
implementation blockboard A blackboard instance.
label The data field.

2.2.6 generic function find-data blackboard label
description/ default Returns the value of a data field for a given label. Does not throw an error but just returns nil if the entry is not found.
implementation blockboard A blackboard instance.
label The data field.

2.2.7 generic function set-data blackboard label data
description/ default Writes some data to a data field. Throws an error if the field does not exist.
implementation blackboard A blackboard instance.
label The data field.
data A new value for that field.

2.2.8 generic function remove-data blackboard label
description/ default Removes both the data and the data-field from the blackboard.
implementation blackboard A blackboard instance.
label The data field.
2.3 Trees

We provide very basic abstractions for creating and maintaining tree-like datastructures.

2.3.1 *structure node*

- **description**: A node contains a parent (which is again a node) and children which is a list of nodes.
- **slot parent**: 
  - (parent nil)
  - Contains the parent of this node. If it is the top of the tree it contains the dummy-top-node (see below).
- **slot children**: 
  - (children nil :type list)
  - A list of children of this node. Of course this can be nil if it is a leaf.

2.3.2 *structure dummy-top-node*

- **description**: A dummy data-type to be able to check for the root (top) of the tree. The actual top has this as parent.

2.3.3 *structure mtree*

- **description**: The actual tree abstraction. Contains all of the nodes and a reference to the actual root.
- **slot nodes**: 
  - (nodes nil :type list)
  - A list of nodes containing all nodes of the tree.
- **slot top**: 
  - (top (make-dummy-top-node) :type node)
  - The actual root (or top) of the tree. Although it is initialised as dummy-top-node it should become the actual root as soon as one node is added.

2.3.4 *generic function has-parent? node*

- **description/default implementation**: Returns true if there is a parent which is not the dummy-top-node.
  - node A node.

2.3.5 *generic function traverse mtree func &key from*

- **description/default implementation**: Traverses the mtree in a depth-first fashion calling func on every node. If from is given (which should be a node in the tree) it will not start from the top but will start from that node.
  - mtree A tree.
func A function which takes one parameter which has to be a node.

from A node from which to start. If not given the top of the tree is taken.

2.3.6 *generic function** leaf? node

description/ default
implementation

Returns true if the node is a leaf, which simply means it has no children.

node A node.

2.3.7 *generic function** top? node

description/ default
implementation

Returns true if the node is the top of a tree, which simply means it has
dummy-top-node as parent.

node A node.

2.3.8 *generic function** leafs mtree

description/ default
implementation

Returns a list of all leafs of the tree. This is thus that subset of the nodes
that have no children.

tree A tree.

2.3.9 *generic function** add-node mtree node &key parent

description/ default
implementation

Adds the given node to the tree. Although it can only do so as a leaf. So
it cannot add a node in the middle of the tree or at the top if there already
is a top. Therefore you have to supply :parent when this is not the first
node added to the tree. The parent has to be valid.

tree A tree.

node The new node that shoud be added to the tree.

parent The node in the tree to which you wish to hang the new node.

2.3.10 *generic function** replace-node mtree old-node new-node

description/ default
implementation

replaces the old node with the new node. It can only replace leaf. Of
course the old-node has to be found in the tree.

tree A tree.

old-node The old node to be replaced.

new-node The node that should replace the old one.
2.3.11  *generic function depth node*

<table>
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<th>description/ default</th>
<th>implementation</th>
</tr>
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<td></td>
<td>Returns the depth of the given node in the tree from which it is part. It is not required to pass the tree itself.</td>
</tr>
<tr>
<td>node</td>
<td>The node form which you wish to know its depth.</td>
</tr>
</tbody>
</table>
3 Monitoring Experiments

The Babel framework contains extensive monitoring and debugging mechanisms that help developers and users to

- print comprehensible traces of the execution of specific components on the screen (e.g. process execution, learning framework, games ...),
- raise warnings or take other actions when specific events happen,
- record and store arbitrary numeric and non-numeric values for each interaction,
- print these data to the screen or write them to a file
- plot these data in real-time using gnuplot or generate graphs offline.

This chapter describes the general monitoring mechanisms, the built-in monitors classes that come with the monitor system, and helps you to use monitors for your own experiments. The monitoring system is defined in directory `systems/monitors`.

3.1 Events, Monitors and Notifications

The main motivation for implementing the monitor system was to separate the source code that does something (running an experiment, running a production task, repairing something, etc) from source code for debugging and data collection. Thereto, a set of “monitors” that subscribe to a set of “events” are defined. In some source code that does something, the monitoring system is “notified” for a specific event. The “active” monitors “handle” that event. Here is an example:

```
(in-package :monitors)

(define-event run-test-finished (result number))

(defun run-test ()
  (let ((result (random 10)))
    ;; do something
    (notify run-test-finished result)
    result))

(define-monitor print-test-result :documentation "prints the result of run-test")

(define-event-handler (print-test-result run-test-finished) 
  (format t "run-test finished. Result: ~a" result))
```
The function `run-test` does something, amongst other things calculating the variable `result`. Let’s assume a developer wants to print the result of function `run-test` whenever it finishes. There is an event `run-test-finished` defined. At the end of function `run-test`, the monitoring system is notified on that event, passing the value of variable `result` as a parameter. Then there is the definition of monitor `print-test-result`, together with an event handler that handles the event for that monitor by printing the result. However, if you run `run-test` like it is, nothing will happen. The monitor needs to be activated:

```lisp
(activate-monitor print-test-result)
```

Only active monitors get notified on their events. This helps you in deciding which information to print, record, plot etc. In this case, the monitor will print:

MONITORS> (run-test)

run-test finished. Result: 6

This seems to be a lot of code to just print the result of function `run-test`. However, you could easily add more monitors that handle the same event:

```lisp
(define-monitor warn-when-test-result-is-7
  :documentation "warns when function run-test returns 7")

(define-event-handler (warn-when-test-result-is-7 run-test-finished)
  (when (= result 7) (warn "function run-test returned 7!!!!")))
```

Or there could be another monitor that plots the result of `run-test` in a graph. The benefit of using the monitor system is that you do not clutter up your functions with code that does not contribute to the computation of the function’s result. Despite that, you get a lot of things “for free”, as you will see in the remainder of this chapter.

The rest of this section describes the macros that define events and monitors, that notify on events, and that activate monitors. If you are interested in the classes and methods that these macros are based on, then you might want to read section 3.3 first.

### 3.1.1 macro `define-event id &rest parameters`

- **description**: Defines an event. This needs to be done before any notification or handler on that event can be defined. Typically, such a definition is put directly before the definition of the function that notifies on that event.
- **id**: The id for that event. A symbol.
- **parameters**: The parameters with that the event is notified. These are lists with a variable name and the type of the parameter. This information is used to check that you pass the right values with a notification. In a handler you can rely on the passed parameters being of these types.
example (define-event game-finished (result symbol)
    (speaker fcg-agent) (hearer fcg-agent))

There could be a notification for this event at the end of a game. The first parameter would have to be a symbol and the other two instances of (derivates of) fcg-agent.

3.1.2 macro define-monitor id &key class

description Defines a monitor. This should happen before any event handlers for that monitor are defined. Typically, monitors and their handlers are in the same source file.

id An id for the monitor. Typically starts with a verb describing the purpose of the monitor, e.g. print-, trace-, record-, plot- etc.

:class The name of the monitor class. As it will be explained in the next section 3.2, there is a big variety of monitor subclasses. The macro define-monitor is used to instantiate all of them. If :class is not provided, the monitor base class monitor is used.

:documentation This should be a short text that helps other users to guess what the monitor does.

other keyword parameters Depending on :class, other keyword parameters are allowed. These are described in detail in section 3.2.

example (define-monitor print-game-result
    :documentation "prints the result of a game")

This defines a monitor based on class monitor (because no :class parameter was provided).

3.1.3 macro define-event-handler (monitor-id event-id) &body body

description Installs a method that handles a specific event for a monitor (or a list of monitors).

monitor-id The id of the monitor that handles the event. Can be also a list of multiple monitor ids. The event is then handled in the same way for these monitors.

event-id The event to handle.

body An expression that handles the event. You can access the parameters using the variable names from the event definition. If you don’t know the event parameters, use function print-all-monitors to get the definition. The monitor instance can be accessed using the variable monitor (see also the example below).
3 Monitoring Experiments

example
(def-event-handler (print-game-result game-finished)
  (format t "~%Game finished. Result: ~a" result))

In the background, this method will be created:
(defmethod handle-game-finished-event
  ((monitor monitor) (monitor-id (eql 'print-game-result))
   (event-id (eql 'game-finished)) (result symbol)
   (speaker fcg-agent) (hearer fcg-agent))
  (format t "~%Game finished. Result: ~a" result))

This basically makes a method that uses all the parameters of the event definition as method parameters.

3.1.4 macro notify event-id &rest parameters

description Notifies the monitor system that an event happened. For all monitors that can handle the event and that are active, the event handler is called. The order in which the handlers are called is not specified.

id The id of the event

parameters Values for parameters of the event. These need to be as specified in the definition of the event. You will get an error if you pass the wrong number of parameters or if the passed values don’t match the parameter types of the event definition.

example (defun run-game ()
  ;; ... do something
  (notify game-finished result speaker hearer))

Don't hesitate to use notify statements in even time-critical code. As you can see below in the macro expansion, it only loops over the active monitors of an event and calls the corresponding handler methods. When there are no active monitors for that event, nothing happens. Please refer to section 3.3 for more details.

(dolist (monitor-id (active-monitors (get-event 'game-finished)))
  (let ((monitor (get-monitor monitor-id)))
    (handle-game-finished-event monitor monitor-id
      'game-finished result speaker hearer))))

3.1.5 macro activate-monitor id &optional active

description Activates a monitor.

id The id of the monitor.

active Defaults to t. When nil, the monitor is deactivated. This can be used to write functions that activate/deactivate a set of monitors together.

3.1.6 macro deactivate-monitor id
3.1.7 \textit{macro} \texttt{toggle-monitor} \textit{id}

\begin{itemize}
\item \textbf{description} Deactivates a monitor.
\item \textbf{id} The id of the monitor.
\end{itemize}

3.1.8 \textit{macro} \texttt{toggle-monitors} \textit{&rest ids}

\begin{itemize}
\item \textbf{description} Toggles (inverses) the activation of a list of monitors.
\item \textbf{ids} A list of monitor ids
\end{itemize}

3.1.9 \textit{macro} \texttt{print-all-monitors}

\begin{itemize}
\item \textbf{description} Prints for all defined monitors their type, whether they are active, the documentation and the source file they are defined in (if possible).
\end{itemize}

3.1.10 \textit{macro} \texttt{print-all-events}

\begin{itemize}
\item \textbf{description} Prints for all defined events the parameter list and the source file they are defined in (if possible).
\end{itemize}

3.1.11 Pre-defined Events

The monitoring system is designed to monitor experiments. Many of the built-in monitor classes do something at the end of interactions, series, or batches (see section 4.2.3). For example updating a plot, writing data to a file or printing something to the screen. They “know” that for example an interaction finished because the experiment framework notifies on these built-in events (section 4.2.3):

3.1.11.1 \textit{monitor event} \texttt{interaction-started} \texttt{(experiment t)}

\begin{itemize}
\item \textbf{description} Notified at the beginning of an interaction.
\item \textbf{experiment} The current experiment (contains the interaction number). The type in this definition is \texttt{t} is because the class \texttt{experiment} is not known yet in the context of the monitor system.
\end{itemize}

3.1.11.2 \textit{monitor event} \texttt{interaction-finished} \texttt{(experiment t) (interaction-number fixnum)}
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3.1.11.3 monitor event series-finished (series-number fixnum)

description At the end of a series.
series-number The number of the finished series (starting from 1).

3.1.11.4 monitor event batch-finished (experiment-class string)

description Notifies that a batch finished.
experiment-class The name of the experiment class.

3.1.11.5 monitor event reset-monitors

explanation You can notify on this event in order to reset the monitor system.

These events are also very handy to define event handlers for your own monitors. For example with the event interaction-finished you get the experiment as a parameter and can record some measures of the rule-sets of the agents of your population.

3.2 Built-in Monitor Classes

You will rarely define monitors of the base class monitor. Instead, you would choose one of the built-in classes that provide a big variety of additional functionalities. Or one of the classes that you defined yourself (see section 3.3.3). Figure ?? gives an overview over the hierarchy of built-in monitor classes.

The rest of this section describes how to use them. Although the different kinds are referred to with their class name, the slots of these classes are not described here (you normally also don’t get in touch with instances of monitors), as monitors of all classes have to be defined with the define-monitor macro (see previous section).

3.2.1 Printing Program Traces

The most common debugging technique when programming lisp is to add format statements to the functions and comment them out when they are not needed anymore. However, this can become quite cumbersome if you want to print different stuff in different situations. The built in “trace
monitors” allow you to toggle printing of information by toggling monitor activation. Additionally, they can buffer text messages and print them later on demand.

3.2.1.1 monitor class trace-monitor monitor

description A monitor for printing text messages to the screen. It is also able to buffer the text (see below).

define-monitor trace-run-test :class 'trace-monitor
 :documentation "Traces the execution of run-test.""

define-event-handler (trace-run-test run-test-finished)
 (format (monitor-stream monitor)
 "run-test finished. Result: ~a"
)

Figure 3.1: The class hierarchy of the built-in monitor classes
3.2.1.2 function activate-buffering-of-trace-monitors

description Switches on buffering. Messages for trace monitors are not printed immediately anymore. Instead, they are kept in a buffer (and can be printed later). This handy feature makes it possible to get to a lot of different traces after something happened without having to print them to the screen beforehand.

example

MONITORS> (activate-buffering-of-trace-monitors)
NIL
MONITORS> (progn (run-test) (run-test))
NIL
MONITORS> (print-buffered-messages-of-trace-monitors)

in the middle of run-test!
run-test finished. Result: 7
in the middle of run-test!
run-test finished. Result: 9

NIL

(for the printing of buffered messages see below)

3.2.1.3 function print-buffered-messages-of-trace-monitors

description Prints all the buffered messages of all trace monitors.

3.2.1.4 function clear-trace-monitors-buffer

description Clears the buffer for the trace monitors. Does not change activation state. In order to avoid the buffer to become very large, it is recommended to call this function often, for example before each interaction.

3.2.1.5 macro deactivate-buffering-of-trace-monitors

description Deactivates the buffering for trace monitors.

3.2.1.6 generic function print-with-overline monitor character message

description/ default implementation Prints a text message in a trace monitor with an overline of the same length as the message (see example below).

monitor An instance of trace-monitor.
character The character to use for printing the overline.
message The message itself. Should not contain line breaks.
### 3.2.2 Recording Data

One of the purposes of running experiments is to output quantitative measures for the emergence of some feature of language, occurrences of some event, properties of the population, and so on. These measures could be plotted to a graph, written to a data file or printed to the screen. One such a measure could be for example communicative success.

To avoid that all plotting, data-writing and printing monitors which want to output communicative success have to collect that measure for themselves, there is the separation of monitors that record data (class `data-recorder`, this section) and monitors that output these recorded data (next sections 3.2.3 and 3.2.4). For example there is only one monitor that records the communicative success. All monitors that output communicative success in some way use the recorded data of that monitor.

#### 3.2.2.1 `monitor class data-recorder monitor`

- **description**: A monitor that records a single value for each interaction. If you run a batch of series, it also keeps the values of each series. For example after a `(run-batch my-experiment 100 3)`, the monitor will have recorded 100 \times 3 values. The values are recorded from message handlers (see below). If the recorded values are numerical, then the data recorder also stores values that are averaged over a window.

- **example**: (define-monitor record-success
  :class 'data-recorder :default-value 0 :average-window 100
  :documentation "records whether the game was a success")

- **:default-value**: The default value to record. Default: 0. If the data recorder did not receive any other value during an interaction, this value will be recorded.

- **:average-window**: The average values will be computed as the arithmetic mean of the last :average-window values. Default: 100. The computation is fast as it does a recursive update after 2 \times :average-window interactions.
recording values  Values are recorded from message handlers. An example:

```lisp
(define-event-handler (record-success game-finished)
  (if (eql result 'succeed)
      (record-value monitor 1)
      (record-value monitor 0)))
```

In the handler, the function `record-value` is used to get the next value into the data recorder. If this function is called multiple times within an interaction, only the last recorded value is stored.

Alternatively, you can use `incf-value` when you want to sum the values of several events during one interaction:

```lisp
(define-event-handler (some-monitor some-event)
  (incf-value monitor some-value))
```

### 3.2.3 Outputting Recorded Data

All monitors that somehow output data recorded by data recorders are derived from this class:

#### 3.2.3.1 monitor class `data-handler` monitor

<table>
<thead>
<tr>
<th>description</th>
<th>An abstract class that provides functionality to access data of data recorders.</th>
</tr>
</thead>
</table>
| example     | `(m:define-monitor my-data-handler :class 'data-handler :data-sources '(record-utterance
  (average record-success)
  record-number-of-lex-stem-rules))` |

This monitor will output the recorded values of the data recorders `record-utterance`, `record-success` and `record-number-of-lex-stem-rules`.

However, it will not make sense to define a monitor of class `data-handler`, as it does not output anything. You will rather use one of the derived classes from below or the next section.

| :data-sources | A list of data recorder ids. These have to be defined before a data-handler on them can be defined. If you want to access the averaged values of a data recorder, you write `(average monitor-id)`, as in the example above. |

| activation | When you activate any monitor that is derived from `data-handler`, all the data recorders that are specified in :data-sources will automatically become activated. |

#### 3.2.3.2 monitor class `data-printer` `data-handler`

| description | A monitor for printing recorded data to the screen. |
example  (m:define-monitor my-experiment-printer :class 'data-printer
  :data-sources '(record-utterance
      (average record-success)
      record-number-of-lex-stem-rules))
  :format-string "~%~d: ~30a ~,2f ~,2f"
  :interval 50)

This monitor prints the interaction number, the utterance, the average
communicative success and the lexicon size to the screen:

```
MY-EXPERIMENT> (run-interactions 500 :reset t)
```

50: (fulele napimu xifibu) 0.08 13.00
100: (monalu) 0.10 20.60
150: (sopogo) 0.12 26.40
200: (zaradu fulele) 0.19 32.20
250: (fenowu foxapu) 0.43 35.20
300: (vazoro kesoku) 0.64 38.40
350: (wunoze) 0.75 40.20
400: (raneni napimu) 0.81 42.20
450: (giwene xifibu) 0.83 43.40

:data-sources See section 3.2.3.1.
:format-string A format string as in format. The first argument to it is the interaction
number. The other arguments are the current values of the data recorders
a specified in :data-sources.
:interval How often the information is printed. Default: 1.

3.2.3.3 monitor class data-file-writer data-handler

description An abstract class for writing recorded data to a file. You can not define
monitors of this class. See the two derived classes below instead.

3.2.3.4 monitor class text-data-file-writer data-file-writer
description Writes recorded data in columns to a text file, which can be imported for
example in Excel. For each data source there is for each series a separate
column.
example  (define-monitor write-success-and-lexicon-size-to-file
  :class 'text-data-file-writer
  :data-sources '((average record-success)
    record-number-of-lex-stem-rules)
  :file-name (make-pathname :directory '(:absolute "tmp")
    :name "success-and-lexicon"
    :type "dat")
  :add-time-and-experiment-to-file-name t
  :column-separator " "
  :comment-string "#")

The text file is written at the end of a batch:

MY-EXPERIMENT> (run-batch 500 3)


The generated file /tmp/2007-03-29-16-25-naming-game-success-and-lexicon.dat looks like this:

# This file was created by the
# text-data-file-writer WRITE-SUCCESS-AND-LEXICON-SIZE-TO-FILE.
# The columns are:
# interaction number
# RECORD_SUCCESS-0
# RECORD_SUCCESS-1
# RECORD_SUCCESS-2
# RECORD_NUMBER_OF_LEX_STEM_RULES-0
# RECORD_NUMBER_OF_LEX_STEM_RULES-1
# RECORD_NUMBER_OF_LEX_STEM_RULES-2
0.0 0.0 0.0 0.0 0.4 0.4 0.4
1.0 0.0 0.0 0.0 0.4 0.8 0.8
2.0 0.0 0.0 0.0 0.8 1.2 1.2
...
498.0 0.9 0.92 0.88 42.8 39.6 47.2
499.0 0.9 0.92 0.88 42.8 39.6 47.2
500.0 0.9 0.92 0.89 42.8 39.6 47.2

:file-name  The name of the file to generate. Should be a pathname.

:add-time-and-
experiment-to-
file-name  When t (default), the current date and time as well as the name of the experiment class are added to the file name.

:column-separator  The string to separate values. Default: " ".

:comment-string  How to start comment lines. Default: "#".

3.2.3.5  monitor class lisp-data-file-writer  data-file-writer
description   Writes the recorded data as a single s-expression to a file. This can be handy if you later want to read the data back to lisp.

example      (define-monitor write-success-and-lexicon-size-to-file
                  :class 'lisp-data-file-writer
                  :data-sources '((average record-success)
                                   record-number-of-lex-stem-rules)
                  :file-name (make-pathname :directory '(:absolute "tmp")
                                     :name "success-and-lexicon"
                                     :type "lisp")
                  :add-time-and-experiment-to-file-name nil)

The resulting text file can be read back with

(with-open-file (stream #P"/tmp/success-and-lexicon.lisp")
               (defparameter data (read stream)))

:file-name     The name of the file to generate. Should be a pathname.

:add-time-and-experiment-to-file-name

---

3.2.4 Plotting Data with Gnuplot

The probably most prominent feature of the monitoring system is to produce graphs from recorded data using gnuplot.

3.2.4.1 monitor class gnuplotter data-handler

description   An abstract class for plotting data with gnuplot. Classes that derive from this one define how the resulting graph is displayed or written.

example      (define-monitor plot-success-and-lexicon-size
                  :class 'CLASS-DERIVED-FROM-GNUPLOTTER
                  :data-sources '((average record-communicative-success)
                                   record-average-number-of-words)
                  :caption '("communicative success" "lexicon size")
                  :minimum-number-of-data-points 500
                  :x-label "number of interactions"
                  :y1-label "communicative success"
                  :y2-label "lexicon size"
                  :error-bars t :draw-y1-grid nil
                  :line-width 2
                  :use-y-axis '(1 2)
                  :y1-max 1 :y1-min 0
                  :y2-min 0 :y2-max nil
                  :colors *great-gnuplot-colors*
                  :key-location "right bottom")
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Figure 3.2: An example for a real-time plot with a gnuplot-display monitor

Depending on what class CLASS-DERIVED-FROM-GNUPLOTTER is, the result might look as in figure 3.2 or figure 3.3.

:data-sources See section [3.2.3.1].

:caption Captions for each data source for generating a graph legend. Should be a list of strings with one caption per data source. When no captions are provided, the names of the data recorders are used.

:minimum-number-of-data-points The “sample rate”. For at least that many points on the x-axis there will be a value plotted. Smaller numbers here result in higher speed and smaller graphic files, bigger numbers give a higher resolution. Default: 500.

:x-label Labels for the x-axis, left y-axis and right y-axis. Default: nil.
:y1-label
:y2-label

:error-bars When true, error bars are added to the graph. Default: nil.

draw-y1-grid When true, thin horizontal lines are drawn at the ticks of the left or right axis. Default: nil.

draw-y2-grid

:line-width The width of the lines for curves and errorbars. Default: 2.

:use-y-axis A list of values 1 or 2 for each data source specifying whether to scale the data with the left y-axis (1) or the right (2). Default: scale all with the left y-axis.
Minimum and maximum values for the left and right y-axis. When not provided, the data is automatically scaled to fit (which is often better).

```
:y1-min :y1-max
:y2-min :y2-max
```

Whether the graph uses colors for different data lines nor not (only has effect on some gnuplot terminals). Default `t`.

```
:colored
```

A list of colors (list of strings, e.g. `'("red", "green")`) to be used by the different graph lines. Defaults to `*great-gnuplot-colors*`.

```
:colors
```

Where to put the graph legend. Possible values are for example "off" (for no legend) "below", "top right", etc. For more information, type "help set key" into gnuplot. Default: "below".

```
:key-location
```

3.2.4.2 monitor class `gnuplot-display` `gnuplotter`

description Plots the data in real-time into a window using gnuplot.

This requires the proper installation of a recent version of gnuplot and a configuration of your lisp environment so that it can find gnuplot. You can test whether your lisp/gnuplot integration works by loading the :utils asdf system and evaluating:

```
-utils:with-open-pipe
  (stream (utils:pipe-output "gnuplot" :args '("-persist")))
  (format stream "plot sin(x)")
  (finish-output stream))
```

This should open a window that shows a sinus plot.

```
example (define-monitor display-success-and-lexicon-size
  :class 'gnuplot-display
  :documentation "Shows communicative success and lexicon size."
  :data-sources '((average record-communicative-success)
                   record-average-number-of-words)
  :caption '("communicative success" "lexicon size")
  :x-label "number of interactions"
  :y1-label "communicative success" :y2-label "lexicon size"
  :error-bars t :use-y-axis '((1 2)
                             :y1-max 1 :y1-min 0 :y2-min 0 :key-location "right bottom")
```

When activating this monitor and for example running `(run-batch 2500 5)` a plot window such as in figure 3.2 will be updated every 50 interactions.

```
:update-interval
```

How often the graph display will be updated. The smaller the value, the slower the whole thing. Default: 10 (very slow).

All other parameters are the same as in section 3.2.4.1.

3.2.4.3 monitor class `gnuplot-graphic-generator` `gnuplotter`
Figure 3.3: An example for a plot generated by a gnuplot-graphic-generator monitor

**description** Produces a graph file at the end of a batch. It is recommended to use such a graph for papers instead of saving the result of gnuplot-display-monitors, as they produce graphic files of much higher quality.

**example**

```lisp
(define-monitor plot-success-and-lexicon-size
  :class 'gnuplot-graphic-generator
  :documentation "Plots communicative success and lexicon size"
  :graphic-type "pdf"
  :colored nil
  :add-time-and-experiment-to-file-name nil
  :file-name (make-pathname :directory '(:absolute "tmp")
    :name "success-and-lexicon-size"
    :type "pdf")
  :data-sources '((average record-communicative-success)
    record-average-number-of-words)
  :caption '("communicative success" "lexicon size")
  :x-label "number of interactions"
  :y1-label "communicative success" :y2-label "lexicon size"
  :error-bars t :use-y-axis '(1 2) :key-location "right bottom"
  :y1-max 1 :y1-min 0 :y2-min 0 :draw-y1-grid t)
```

The resulting file `/tmp/success-and-lexicon-size.pdf` looks as in figure 3.3.

**graphic-type** Which gnuplot graphic driver to use. Should be one out of "postscript", "pdf", "svg" or "gif".

**file-name** The file name of the graphic file to produce. Should be a pathname.
3.2.4.4 *monitor class* **gnuplot-display-and-graphic-generator** **gnuplot-display** **gnuplot-graphic-generator**

**description** A monitor that produces a real-time plot and generates a graphic file in the end.

As it derives from both of these classes, it takes all parameters that **gnuplot-display** and **gnuplot-graphic-generator** take.

3.2.4.5 *monitor class* **gnuplot-file-writer** **gnuplot-graphic-generator**

**description** If you don’t like the graphs that the **gnuplot-graphic-generator** makes, you can also use this monitor to write a complete gnuplot script (with data and plot commands) and later modify that script. The parameter **:gnuplot-file-name** specifies the file name of the script.

3.2.5 **Recording and Plotting Lists of Data**

Data recorders (section 3.2.2.1) allow to record one single value for each interaction. But sometimes one wants to look at the evolution of a list of values, for example the scores of some entities or the number of occurrences of events. Defining a data recorder for each of them would become cumbersome, especially if the number of values is not known beforehand. For this purpose, there are monitors for recording and processing lists of data.

3.2.5.1 *monitor class* **alist-recorder** **monitor**

**description** Records averaged values for lists of (symbol . value) conses. Similar to a **data-recorder** (section 3.2.2.1), values are kept for each interaction of each series of a batch.

**example**

```
(define-monitor record-lexicon-of-first-agent-for-first-object
  :class 'alist-recorder
  :documentation "Records for the first agent the scores of all words for the first object"
  :average-window 1)
```

**:average-window** The values will be averaged over the last **:average-window** values. Default: 100.
Values are recorded from event handlers. An example:

```
(define-event-handler
  (record-lexicon-of-first-agent-for-first-object
   interaction-finished)
  (loop with rules
    = ;; compute the rules of the first agent that have first
    ;; object of the world as meaning
    for rule in rules
    do (set-value-for-symbol monitor
        (intern (word rule))
        (rule-score rule)))
```

The function `(set-value-for-symbol monitor symbol value)` is used to store the rule score for each rule in the monitor, with symbol being the interned rule name. Each time you pass a value for a new symbol, a new list of recorded values is created. If you don’t pass a value for some symbol during an interaction, the value 0 is recorded. Alternatively, you can use the function `(incf-value-for-symbol monitor symbol value)` to increase the current value for a symbol, starting in each interaction from 0.

### 3.2.5.2 monitor class `alist-handler` monitor

**description** The base class for all monitors that do something with data recorded by a `alist-recorder`.

**:recorder** The id of the `alist-recorder` to use. That recorder will become automatically activated whenever a monitor derived form `alist-handler` gets activated.

### 3.2.5.3 monitor class `alist-printer` `alist-handler`

**description** Prints the values of an alist recorder after each interaction.
example (define-monitor print-lexicon-of-first-agent
   :class 'alist-printer
   :documentation "Prints for the first agent the scores of all
   words for the first object"
   :recorder 'record-lexicon-of-first-agent-for-first-object
   :interval 100)

When this monitor is active, the output of a batch looks like this:

MY-EXPERIMENT> (run-batch *experiment* 1000 1)

100: vewiba: 0.50; sowape: 0.50;
200: vewiba: 0.50; sowape: 0.50;
300: vewiba: 0.50; sowape: 0.50;
400: vewiba: 0.60; sowape: 0.30;
500: vewiba: 0.80; sowape: 0.00; bofoxa: 0.10;
600: vewiba: 1.00; sowape: 0.00; bofoxa: 0.00; fapofo: 0.10;
700: vewiba: 0.90; sowape: 0.00; bofoxa: 0.00; fapofo: 0.00;
800: vewiba: 0.80; sowape: 0.00; bofoxa: 0.00; fapofo: 0.00;
900: vewiba: 0.90; sowape: 0.00; bofoxa: 0.00; fapofo: 0.00;
1000: vewiba: 0.80; sowape: 0.00; bofoxa: 0.00; fapofo: 0.10;
NIL

:recorder See section [3.2.5.2]
:interval The data is printed only every :interval interactions. Default: 1.

3.2.5.4 monitor class alist-gnuplotter alist-handler

description The base class for plotting data recorded by an alist-recorder with
gnuplot.

example (define-monitor plot-all-words-for-first-object
   :class 'CLASS-DERIVED-FROM-ALIST-GNUPLOTTER
   :documentation "Plots scores of all words for the first object"
   :recorder 'record-all-words-for-first-object
   :minimum-number-of-data-points 500
   :error-bars nil
   :key-location "below"
   :y-min 0 :y-max 1.05 :draw-y-grid t
   :y-label nil x-label nil
   :line-width 1 :draw-y-grid t
   :colors '("red" "blue" "black" "green" "gold")

Depending on what CLASS-DERIVED-FROM-ALIST-GNUPLOTTER is, the re-
sult might look like in figure [3.4] or figure [3.5]

:recorder See section [3.2.5.2].
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Figure 3.4: An example for a real-time plot with a **alist-gnuplot-display** monitor

:minimum-number-of-data-points
:errorbars
:colors
:line-width
:key-location
:y-min :y-max

See section 3.2.4.1

The minimum and maximum y values. When not provided, the graph is automatically scaled (which is often better).

:draw-y-grid

When t, thin horizontal lines are drawn at the height of the y ticks.

3.2.5.5 **monitor class** **alist-gnuplot-display** **alist-gnuplotter**

description

Displays plots of data recorded by an **alist-recorder** in real-time.

example

`(define-monitor display-all-words-for-first-object
 :class 'alist-gnuplot-display
 :documentation "Plots scores of all words for the first object"
 :recorder 'record-all-words-for-first-object
 :draw-y-grid t :y-max 1.05 :y-min 0
 :update-interval 25)

The resulting graph looks as in figure 3.4.`
Figure 3.5: An example for a plot generated by a *alist-gnuplot-graphic-generator* monitor

:\textbf{update-interval} \ How often the display is redrawn. Default: 100.

All other parameters are as described in section 3.2.5.4

3.2.5.6 \textit{monitor class} \textbf{alist-gnuplot-graphic-generator} \textbf{alist-gnuplotter}

\textbf{description} \ Produces a graph file at the end of a batch. It is recommended to use such a graph for papers, as they are black and white.

\textbf{example} \ (define-monitor plot-all-words-for-first-object
  :class 'alist-gnuplot-graphic-generator
  :documentation "Plots scores of all words for the first object"
  :recorder 'record-all-words-for-first-object
  :draw-y-grid t :y-max 1.05 :y-min 0
  :file-name (babel-pathname :directory (list "tmp")
    :name "lexicon" :type "ps")
  :add-time-and-experiment-to-file-name nil
  :graphic-type "postscript")

The resulting file /tmp/lexicon.ps looks as in figure 3.5.
3 Monitoring Experiments

graphic-type Which gnuplot graphic driver to use. Should be one out of "postscript", "pdf", "svg" or "gif".

:file-name The file name of the graphic file to produce. Should be a pathname.

:add-time-and-experiment-to-file-name See section 3.2.3.4.

All other parameters are the same as in section 3.2.5.4.

3.2.5.7 monitor class alist-gnuplot-display-and-graphic-generator alist-gnuplot-display alist-gnuplot-graphic-generator

description A monitor that produces a real-time plot and generates a graphic file in the end.

As it derives from both of these classes, it takes all parameters that alist-gnuplot-display and alist-gnuplot-graphic-generator take.

3.3 Behind the Scenes

As mentioned in the beginning of section 3.2, you will normally not get in touch with the classes that form the base of the monitor system. Instead, you will use the macros from section 3.1. However, if you want to define some monitors that do something else than what you can do with the built-in monitors and if you want to reuse this functionality, you might want to derive your own monitor classes.

This section describes the monitor, event, and event handling base classes and methods that are defined in systems/monitors/base.lisp. You can easily skip this section if you are only interested in using the monitors.

Please note that all the classes and methods are not exported from the :monitors package as they are “hidden” from the user. It is recommended to put your own classes in that package too.

3.3.1 Classes for Monitors and Events

3.3.1.1 class monitor

description The base class for all monitor classes. Stores the events that a monitor is subscribed to and whether the monitor is active.

slot id A unique id.

slot event-ids The ids of events that the monitor is “subscribed” to. Technically, these are all events for that an event handler was defined.
3 Monitoring Experiments

slot active If t, then this monitor is notified on its events.

slot documentation A string that helps the user to guess the purpose of the monitor.

slot source-file The file in that the monitor was defined. This is guessed using the LISP variable *load-pathname*, which not always contains a file name.

slot init-arguments The keyword parameter list with that the monitor was defined. This is stored in order to be able to redefine a monitor only when its parameters change.

slot error-occured-during-initialization When t, an error occured during the initialization. This information is stored for determining when to redefine a monitor.

3.3.1.2 class event

description Represents an event with its parameters and a list of monitors that are listening to the event.

slot id An unique event id.

slot active-monitors A list of the ids of those monitors that subscribed to this event and that are active.

slot source-file The file in that the event was defined. This is guessed using the LISP variable *load-pathname*, which not always contains a file name.

slot parameters A list of (name type) parameter definitions, used for method generation.

3.3.1.3 global variable *monitors*

description A hash table containing the instances of all defined monitors. When a monitor is defined with define-monitor, the instance is automatically stored there. Due to that, the user does not have to care about keeping pointers to these instances and it is easier to access a particular monitor, for example for activating it.

3.3.1.4 global variable *events*

description A hash table containing the instances of all defined events.

3.3.1.5 function get-monitor id

description Returns the monitor instance for an id. Normally you will never do this but it helps for example when you want to see what kind of data a data-recorder recorded.

id The id of the monitor.
3.3.1.6 function get-event id

description Returns the event instance for an id.

id The id of the event.

3.3.2 The Creation of Monitors, Events and Handlers

To prevent the user from being confronted with the classes above and in order to guarantee some properties of monitors and events, there is a lot of checking going on. In :around methods of initialize-instance, it is checked for almost every parameter whether the passed values are correct. You will normally get helpful error messages if you passed something wrong.

For convenience, when a source file is recompiled or reloaded, the state of the contained monitors and events is preserved. For that, monitors copy the state of previous instances in the initialize-instance :around methods. Additionally, monitors and events are only redefined when there is no previous instance or when parameters changed:

3.3.2.1 function make-monitor-unless-already-defined id class &optional init-arguments

description Makes a new monitor when there is (1) no previously defined monitor with the same id, (2) the arguments passed to the monitor (init-arguments) are different from a previous monitor with the same id, or (3) an error occurred during the initialization of the previous monitor.

id The id of the monitor.

class The class to instantiate.

init-arguments All keyword parameters that are needed to make the instance.

3.3.2.2 function subscribe-to-event monitor-id event-id

description Adds an event to the event-ids list of a monitor. When the monitor is a active, it is also added to the active-monitors slot of the event.

monitor-id The id of the monitor.

event-id The id of the event.

3.3.2.3 function make-event-unless-already-defined id parameters
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description Makes an event (only when it is not defined yet or when parameters changed). Additionally, it defines a generic function for handling the event. For example for event interaction-started, this generic function is generated, incorporating the passed parameters:

(defgeneric handle-interaction-started-event
  (monitor monitor-id event experiment))

There is a default implementation that specializes on \textit{t} for the parameters of the event. If you type for example (notify interaction-started 42), then that method will give you this error:

Parameter 2 (EXPERIMENT) should be of type EXPERIMENT. Instead, 42 (FIXNUM) was passed.

[Condition of type SIMPLE-ERROR]

\textbf{id} The id of the event.

\textbf{parameters} The parameter list.

3.3.2.4 \textit{function} make-event-handler \textit{monitor-id} \textit{event-id} \textit{body}

\textbf{description} Subscribes a monitor to an event (using subscribe-to-event, section 3.3.2.2) and creates an event handler method.

\textbf{monitor-id} The id of the monitor. Either a symbol or a list of symbols (for defining multiple handlers at the same time).

\textbf{event-id} The id of the event to handle.

\textbf{body} The body of the handler method (see section 3.1.3).

In order to put events and their handlers into the same source file, the events and monitors have to be defined at macro expansion time (the macro expansion of the \textit{notify} macro (section 3.1.4 needs to know the parameters of the event to generate the method call). But as there is no macro expansion when a compiled file is loaded, the events also have to be defined at load time.

This problem is solved by defining each event and monitor twice:

( defmacro define-event \textit{id} \&rest \textit{parameters} )
  ( make-event-unless-already-defined \textit{id} \textit{parameters} )
  ( make-event-unless-already-defined \textit{',id ',parameters} )

The first line is executed during macro expansion when a source file is compiled. The second line will be executed as well but does not do anything because the event is already defined. When loading a compiled file, only the second line was compiled into the code and is executed. The same thing happens in the \textit{define-monitor} macro.
3.3.3 Defining own Monitor Classes

This section shows how to derive own monitor classes. The existing class `trace-monitor` (section 3.2.1.1) serves as an example. The first thing to do is to derive an own class from one of the built-in monitor classes and define some slots that the monitor will need to function (there are no slots needed in this example):

```lisp
(defun trace-monitor (monitor)
  ()
  (:documentation "Prints string messages on a screen or keeps them in a shared buffer for later retrieval"))
```

The next thing is to define the initialization of the monitor instance. This typically looks like this:

```lisp
(defun initialize-instance :around ((monitor trace-monitor) &key id &allow-other-keys)
  (let ((previous-monitor (get-monitor id)))
    (call-next-method)
    (setf (error-occured-during-initialization monitor) t)
    (make-event-unless-already-defined id '((message string)))
    (when (or (not previous-monitor)
              (error-occured-during-initialization previous-monitor)
              (not (find id (event-ids monitor))))
      (make-event-handler
       id id '((unless (equal ,,(intern-in-package-of id "MESSAGE") ")")
           (format (monitor-stream monitor) "%a" ,,(intern-in-package-of id "MESSAGE"))))))
    (setf (error-occured-during-initialization monitor) nil))
```

Before the base class is initialized with `(call-next-method)`, a reference to the old monitor instance is kept in variable `previous-monitor`. Then, the monitor slot `error-occured-during-initialization` is set to `t`. This is set to false again in the last line. If something goes wrong between these two lines, the value of that slot remains `t` so that the next attempt to initialize starts from scratch again.

Then there is automatically an event defined that has the same name as the monitor and takes a string as parameter. Only when there is no previous monitor, when there were no errors and when there is no handler yet for that automatically generated event, an event handler that prints or buffers the message is defined using the `make-event-handler` macro.
4 The Experiment Framework

This chapter defines what an “experiment” is in the Babel framework. There is a “population” of agents that engage in “interactions”. An agent is understood as a software entity that interacts with a “world” (see for example Russel and Norvig [1995] has an internal state, own goals and means to achieve them. It perceives information from the world and performs “actions” on it. It has ways to diagnose problems in its information processing and repair strategies to adapt and optimize its state and processing. Agents can not look into each others brains, which means that they never can access the internal states of others. Instead, they perform actions such as speaking or pointing that are observed by the other agents. An experiment itself is a controlled repetition (batch) of series of such interactions. For each series, measures of the emergent behavior or properties of the agent’s information processing are recorded.

The experiment framework defined the concepts introduced above in a rather abstract way. Specific kinds of experiments such as different types of language games are operationalized by subclassing and implementing generic methods described in this chapter.

4.1 Agents Situated in the World

This section defines agents and their interaction with the world.

4.1.1 Actions Performed on the World

Actions are performed by agents. They can change the state of the world and are observable by other agents. They can be anything that a robot or a human could do, for example speaking, pointing, giving, walking, nodding, etc – but rather no telepathic or other supernatural activities.

4.1.1.1 class action

description Represents an action performed by an agent. You define own actions by subclassing from action.

slot agent-id (agent-id :type (or symbol fixnum) :initform nil :initarg :agent-id :accessor agent-id)

The id of the agent that does the action. Normally you will not have to provide this when creating an action because it is set automatically in an :around method of run-agent (see section 4.1.2.2).

1 See also the source files in directory systems/experiment-framework.
The ids of the agents that the action is directed to. By default, the action is performed to all interacting agents (value '(all-agents)).

4.1.1.2 class no-action action

description When an agent performs this action it means that it waits for other agents to do something or that it believes the current interaction to be finished.

4.1.1.3 class world

description The state of the shared world in which the agents are interacting. It is highly experiment dependent what that is. Normally you will define a world for your experiment by subclassing from world.

slot actions (actions :type list :initform nil :accessor actions)

All actions that were performed by the agents during the current interaction. Newer actions are first in the list. These are added automatically by the framework after update-world (see below).

4.1.1.4 generic function initialize-world-for-next-interaction world

description Initializes or updates the state of the world at the beginning of a new interaction. It is called automatically in an :around method of run-interaction (see section 4.2.2.3).

world The world to initialize.

default implementation The default implementation is empty, because there might be experiments where the world does not have state except the actions performed by the agents. In a :before method, the actions slot of the world is set to nil.

4.1.1.5 generic function update-world world action

description Updates the world dependent on the last action of an agent. It is automatically called from run-interaction (see section 4.2.2.3). If in your experiment the agents perform actions that can change the state of the world, then you would implement a method for your world and action class.

world The world to update.

action The action
4.1.2 Running Agents

The agents that take part in an interaction are run one after the other to determine their next action (see figure 4.1).

4.1.2.1 class agent object-with-learning-mechanisms

description The base class for all agents. It inherit slots for learning mechanisms from base class object-with-learning-mechanisms (see section 4.3).

slot id (id :initarg :id :reader id :type (or symbol fixnum) :initform (gen-sym))

The id of the agent.
slot problems (problems :type list :initform nil :initarg :problems :accessor problems)

All the problems that were encountered during an interaction.

slot list-of-interacting-agents (ids-of-interacting-agents :initform nil :type list :accessor ids-of-interacting-agents)

The ids of all other agents that are part of the current interaction (see section 4.2.2.1).

4.1.2.2 generic function run-agent agent world

description Plans and performs the next action of an agent. Called by run-interaction (see section 4.2.2.3).

agent The agent to perform the action.

world The state of the world including the actions performed by the other agents.

default implementation The default implementation calls repeatedly

• plan-action (see section 4.1.2.3 below)
• run-agent-diagnostics (see chapter 5)
• and run-agent-repair-strategies (see chapter 5)

in a loop until nothing is repaired anymore by the repair strategies (run-agent-repair-strategies returns nil). Then the last planned action is passed to perform-action (see section 4.1.2.5) and the action returned by that is returned by run-agent.

For example there could be an agent that tries to interpret an utterance. First plan-action runs an interpretation task that fails and returns two values, the returned planned action which is a ‘signal failure’ action and a list of agent level learning situations, e.g. (agent-interpreting). Based on these learning situations there are learning mechanisms that repair the agent. Again plan-action is run and this time returns a ‘signal success’ action. This action is passed to perform-action, which commits the things previously learned and updates its linguistic inventory based on the communicative success.

In an :around method, there are notifications for the events run-agent-started and run-agent-finished (sections 4.1.2.6 and 4.1.2.7).

4.1.2.3 generic function plan-action agent world
description Plans an action for the agent based on the world (which contains the actions performed by the other agents). Returns an instance of action and a list of agent level learning situations for that the agent level learning mechanisms are run.

This function is called from run-agent, which runs learning mechanisms after it and, if something is repaired, runs plan-action again. So the action you return here is not necessarily the one that is returned by run-agent. If you want to do something based on the action that the agent actually performs, then you can do that in method perform-action (see below).

agent The agent that is run.

world The world that the agent is situated in.

default implementation There is a default implementation that calls plan-action-based-on-last-action (see below) on the last action of the world. However, this might be not a good idea when there are more than two agents interacting and when actions depend on more than just the action of the last agent that was run. In this case you might consider re-implementing this method for your agent class.

4.1.2.4 generic function plan-action-based-on-last-action agent world last-action

description Returns an action based on a single last action performed by an (the) other agent. When you use the default implementation of plan-action, then you have to implement this method for all actions that your agents can perform. Just as plan-action it also has to return a list of learning situations as second value.

agent The agent that performs the action.

world The world in that the agent is situated.

last-action The last performed action of a (the) other agent.

4.1.2.5 generic function perform-action agent planned-action

description Called by the default implementation of run-agent on the planned action after nothing is repaired anymore. Returns an action. This gives you the chance to do something based on the action that the agent performs.

agent The agent that performs the action.

planned-action The action that was returned by the last call to plan-action.

default-implementation The default implementation simply returns the planned-action.
4.1.2.6 *monitor event* run-agent-started (agent agent) (world world)

- **description**: Triggered at the begin of run-agent.
- **agent**: The agent that is run.
- **world**: The world in the agent is situated.

4.1.2.7 *monitor event* run-agent-finished (agent agent) (world world) (action action)

- **description**: Notified at the end of run-agent.
- **agent**: The agent that performed an action.
- **world**: The world (not yet updated on the action).
- **action**: The performed action.

4.1.2.8 *generic function* initialize-interaction agent

- **description**: Is called for each of the interacting agents at the begin of an interaction. For example can be used to initialize the role that an agent takes in the interaction. The default implementation is empty.
- **agent**: The agent to initialize.

4.1.2.9 *generic function* consolidate-agent agent

- **description**: Is called for each of the interacting agents at the end of an interaction. It is intended to be used for committing learned things or updating scores of inventories. The default implementation is empty.
- **agent**: The agent to consolidate.

4.2 **Interacting Agents**

The main purpose of the experiment framework is to have agents interacting with each other and learn from that. This section describes how these interactions are defined and run.

4.2.1 **Experiments and Populations**

Experiments determine how interactions between agents of a population are run.
description The base class for all experiments. It also contains learning mechanisms as it is derived from object-with-learning-mechanisms (see section 4.3).

slot population (population :type list :accessor population)
A list of agents. The population is automatically initialized when the experiment is created (using the generic function initialize-population, see below).

slot interaction-number (interaction-number :type fixnum :initform 0 :accessor interaction-number)
A counter that is increased with every interaction.

slot interacting-agents (interacting-agents :type list :initform nil :accessor interacting-agents)
A list of the agents that are involved in the current interaction. Determined by function determine-interacting-agents (see section 4.2.2.1).

slot processing-strategies (processing-strategies :type t :initform t :accessor processing-strategies :initarg :processing-strategies)
An experiment specific object that can be used to specialize methods on lower levels. These can be methods that you have to implement for your own experiment. There are also built-in methods that provide multiple options for some particular processing. By deriving your processing strategy from

slot world (world :type world :initarg :world :accessor world :initform (make-instance 'world))
The world that is shared by the agents.

4.2.1.2 generic function initialize-population experiment
description Replaces all agents of an experiment’s population by a new list of agents. The new list should contain at least one agent. In an :after method, all learning mechanisms and processing mechanisms of the experiment are automatically copied into each agent. Additionally, there is a notification for event population-initialized (see below).

You have to implement this method for your experiment.

example (defclass my-experiment (experiment) ())
(defclass my-agent (agent) ())

(defun initialize-population ((experiment my-experiment))
  (setf (population experiment)
        (loop for n from 1 to 5
              collect (make-instance 'my-agent :id n))))
4.2.1.3 *monitor event* **population-initialized** *experiment*

<table>
<thead>
<tr>
<th>description</th>
<th>Triggered after <em>initialize-population</em>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>experiment</em></td>
<td>The experiment for that the population was initialized.</td>
</tr>
</tbody>
</table>

### 4.2.2 Running an Interaction

An “interaction” is when some agents are drawn from the population and interact for some time in a shared world. This could be for example a guessing game where one agent of the population becomes a speaker, describes a scene to a hearer, the hearer points to a thing in the world, and the speaker signals the communicative success of the interaction.

#### 4.2.2.1 *generic function* **determine-interacting-agents** *experiment*

<table>
<thead>
<tr>
<th>description</th>
<th>Called at the begin of each interaction to determine which agents (a subset of the population) will interact with each other. The function has to set the <em>interacting-agents</em> slot of <em>experiment</em>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>experiment</em></td>
<td>An experiment instance.</td>
</tr>
<tr>
<td><em>default</em> implementation*</td>
<td>The default implementation randomly selects two agents from the population of <em>experiment</em>.</td>
</tr>
<tr>
<td></td>
<td>In an :around method, the <em>ids-of-interacting-agents</em> slots of all interacting agents are set properly so that each agent knows with who it is interacting. There is a notification for event <em>interacting-agents-determined</em> (see below).</td>
</tr>
</tbody>
</table>

#### 4.2.2.2 *monitor event* **interacting-agents-determined** (*experiment* *experiment*)

<table>
<thead>
<tr>
<th>description</th>
<th>Triggered at the end of <em>determine-interacting-agents</em>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>experiment</em></td>
<td>The experiment.</td>
</tr>
</tbody>
</table>

#### 4.2.2.3 *generic function* **run-interaction** *experiment*

<table>
<thead>
<tr>
<th>description</th>
<th>The most important function of the experiment framework. Runs one interaction of an experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>experiment</em></td>
<td>The experiment to run.</td>
</tr>
</tbody>
</table>
It is not recommended to specialize this function for your experiment class as there is already a sophisticated default implementation for class `experiment` itself. The default implementation calls the `run-agent` method (see section 4.1.2.2) of the first interacting agent. The returned action is passed to `update-world` (section 4.1.1.5). Then the `run-agent` method of the next agent is called and so on until no agent returns an action different from `no-action` (section 4.1.1.2). See also figure 4.1.

```lisp
(defun run-interaction ((experiment experiment))
  (loop for at-least-one-agent-returned-an-action = nil
    do (loop for agent in (interacting-agents experiment)
           for action = (run-agent agent (world experiment))
           do (unless (typep action 'no-action)
                (setf at-least-one-agent-returned-an-action t))
           (update-world (world experiment) action))
  while at-least-one-agent-returned-an-action)
```

In an :around method,

- the `interaction-number` of the experiment is increased,
- there is a notification on the event `interaction-started` (see section 3.1.11.1),
- the method `called-before-run-interaction` is called (see below),
- `determine-interacting-agents experiment` is called (see above),
- for each interacting agent `initialize-interaction` (section 4.1.2.8) is called,
- the world is initialized with `initialize-world` (section 4.1.1.4),
- the main method is called,
- for each interacting agent `consolidate-agent` (section 4.1.2.8) is called,
- `called-after-run-interaction` (see below) is called,
- there is a notification for event `interaction-finished` (see 3.1.11.2).

### 4.2.2.4 generic function called-before-run-interaction experiment

- **description**: The method is called automatically before `run-interaction`.
- **experiment**: The experiment instance.
- **default implementation**: There is a default implementation that does nothing. You can, but don’t have to, do additional things here such as initializing variables, interacting with robots, etc.

Of course you could also write a :before method for `run-interaction` (it would be the same), but maybe implementing this method for your experiment class makes things look more clear.
4.2.2.5 *generic function* **called-after-run-interaction** *experiment*

description The same as *called-before-interaction*. except that it is called automatically after *run-interaction*.

experiment The experiment instance.

---

4.2.3 Running Experiments

There are three different levels of running an experiment:

- An interaction, see previous section [4.2.2].
- A “series” is a set of subsequent interactions, possibly with different agents of the population participating in the interaction each time.
- A “batch” is a repetition of series with same length. Before each series, the population is reset. This is enables you to average experimental results over many repetitions.

4.2.3.1 *generic function* **run-series** *experiment number-of-interactions &key reset*

description Runs a series of interactions.

experiment The experiment instance.

number-of-interactions How many interactions to run.

:reset Whether to reset the population and the monitors. Default: nil.

default The default implementation executes the *run-interaction* method *number-of-interaction* times. When :reset is t, in the beginning it sets the interaction-number of the experiment to 0, resets the monitors by notifying on the event reset-monitors (section 3.1.11.5) and calls the initialize-population method (section 4.2.1.2).

4.2.3.2 *generic function* **run-batch** *experiment number-of-interactions number-of-series*

description Runs a batch (multiple series of interactions).

experiment The experiment instance.

number-of-interactions How many interactions to run.

number-of-series How many series to run.
default implementation The default implementation resets the monitors in the beginning. Then it runs number-of-series times a series of number-of-interactions interactions, each time in the beginning setting the interaction-number to 0 and resetting the population. After each series, the event series-finished is triggered. In the end, there is a notification for batch-finished.

4.2.3.3 *monitor trace-interaction* trace-monitor

description Prints information about interactions such as the interaction number, which agent is run and which actions it returned.

4.2.3.4 *monitor trace-experiment* trace-monitor

description Prints information about the experiment, when the population is reset and when a series or a batch is finished. Good for observing the progress in large-scale simulations.

4.3 Learning Mechanisms

Learning mechanisms are deeply grounded into the Babel framework. They consist of three things:

1. “diagnostics” reside on top of cognitive processes and try to detect failures or suboptimal processing, which they report in the form of

2. “problems”. They contain the information that can be used by

3. “repair strategies” to overcome failures or to optimize information processing.

Since learning is crucially important we have dedicated a chapter to accommodate all there is to know about learning in the Babel framework. We refer you to chapter 5.

4.4 An Interaction Example

This section shows a very minimal experiment without learning mechanisms that illustrates the concepts described in this chapter. An interaction in this experiment will be that one agent asks for chocolate, gets chocolate and thanks the other agent for it.

First, we define an experiment class, an agent class and an initialization of the population:

```
(defclass my-experiment (experiment) ())
(defclass my-agent (agent) ())

(defmethod initialize-population ((experiment my-experiment))
  (setf (population experiment)
    (loop for i from 1 to 5 collect (make-instance 'my-agent :id i))))
```
We use the default implementation of `determine-interacting-agents` (which randomly selects two agents of the population). We define the two actions that we need for this interaction:

```
(defclass give-action (action)
  ((object :initarg :object :accessor object)))

(defclass speak-action (action)
  ((utterance :initarg :utterance :accessor utterance)))
```

Then we implement the `plan-action-based-on-last-action` methods for `my-agent` and the actions above:

```
(defmethod plan-action-based-on-last-action ((agent my-agent) (world world)
  (last-action (eql nil)))
  (make-instance 'speak-action :utterance "Want chocolate!"))

(defmethod plan-action-based-on-last-action ((agent my-agent) (world world)
  (last-action speak-action))
  (if (string-equal (utterance last-action) "Want chocolate!"
        (make-instance 'give-action :object 'chocolate
                        :recipient-ids (list (first (ids-of-interacting-agents agent)))))
        (make-instance 'no-action)))

(defmethod plan-action-based-on-last-action ((agent my-agent) (world world)
  (last-action give-action))
  (make-instance 'speak-action :utterance "Thank you!"))

(defmethod plan-action-based-on-last-action ((agent my-agent) (world world)
  (last-action no-action))
  (make-instance 'no-action))
```

The first `plan-action-based-on-last-action` method above is run at the begin of an interaction (there are no last actions). The agent that is run first says “want chocolate”. Then the next agent is run. If it hears “want chocolate!”, then it gives chocolate to the other agent. An agent that gets chocolate says “Thank you!”. Whenever the other agent did nothing, an agent also does nothing.

This makes an instance of the experiment:

```
(defparameter *experiment* (make-instance 'my-experiment))
```

To see some output, we activate the monitor `trace-interaction` and then run one interaction:

```
(activate-monitor trace-interaction)
(run-interaction *experiment*)
```

This is the output:

```---
= Started interaction 1.
= Interacting agents: (<my-agent 3> <my-agent 4>)
==
```
4.5 Running Parallel Series of Experiments

Experiments that involve grammar learning, rich conceptualization mechanisms or excessive search can be very slow or can require large number of interactions for the desired phenomenon to emerge. Especially running multiple series of the same experiment in order to have averaged results (running batches) can take forever on a single processor.

Our experiment framework provides one mechanism for speeding this up: multiple series of the same experiment can be run in parallel on a machine that has multiple processors. So far this works only on SBCL and only on machines where different sub-processes are automatically scheduled, but it is very likely that other Lisps and machine architectures will be supported in the future.

Furthermore, there are functions for analyzing the impact of different configurations on a particular measure within one graph.

The functions for parallel batches are defined in `systems/experiment-framework/parallel-batch.lisp`.

4.5.1 function run-parallel-batch &key ...
Figure 4.2: An example for a graph created with `run-parallel-batch`. This is the same graph that also would be created with `run-batch`, except that it is faster to use `run-parallel-batch`.

**description**

The same as method `run-batch` (see section 4.2.3.2), with the difference that each series is run in parallel. Internally it starts for each of the series a separate client Lisp process and then loads and runs a specified experiment in it. The results of each series are then collected and graphs are produced.

**:asdf-system**

The asdf system of the experiment to run.

**:package**

The package to run the experiment in.

**:experiment-class**

The experiment to run.

**:number-of-interactions**

How many interactions to run in each client.

**:number-of-series**

How many series to run. This also determines also how many client Lisp processes will be started. When for example your machine has 10 processors and **:number-of-series** is 10, then each of these processes will be run at 100% CPU usage, speeding up the batch to take only 10% of the time of a serial batch on a single processor. When there are only 5 processors, then each Lisp will run at 50%, speeding up the batch to take 20% of the time.

**:monitors**

Which monitors to use (a list of strings). This can be any kind of monitor, but it makes sense only for those that use data recorders, e.g. gnuplot monitors or data writers.
example

(run-parallel-batch
 :asdf-system "babel-demo"
 :package "babel-demo"
 :experiment-class "naming-game"
 :number-of-interactions 2000
 :number-of-series 10
 :monitors '("babel-demo::plot-success+lexicon-size"))

This has the same effect as running

(asdf:operate 'asdf:load-op :babel-demo)

(in-package :babel-demo)

(activate-monitor babel-demo::plot-success+lexicon-size)

(run-batch (make-instance 'naming-game) 2000 10)

, except that it takes only 10% of the time. The resulting graph is shown in figure 4.2

4.5.2 function create-graphs-for-different-experimental-conditions &key ...

description Creates graphs for the impact on different experimental conditions on particular measures. Different conditions are implemented as separate experiment classes that are then run one after each other, with the results merged into one graph.

example When there is for example an experiment class naming-game, different conditions that analyze different strategies for lexicon update can be created by subclassing from naming-game and then setting different configurations during the initialization:

(defclass ng-1 (naming-game) ())
(defclass ng-2 (naming-game) ())
(defclass ng-3 (naming-game) ())

(defmethod initialize-instance :after ((experiment ng-1) &key)
 (set-configuration experiment 'word-score-delta-success 0.0)
 (set-configuration experiment 'word-score-delta-inhibit 0.0)
 (set-configuration experiment 'word-score-delta-fail 0.0))

(defmethod initialize-instance :after ((experiment ng-2) &key)
 (set-configuration experiment 'word-score-delta-success 0.1)
 (set-configuration experiment 'word-score-delta-inhibit 0.0)
 (set-configuration experiment 'word-score-delta-fail -0.1))

(defmethod initialize-instance :after ((experiment ng-3) &key)
 (set-configuration experiment 'word-score-delta-success 0.1)
 (set-configuration experiment 'word-score-delta-inhibit -0.2)
 (set-configuration experiment 'word-score-delta-fail -0.1))
Figure 4.3: Examples for graphs create by create-graphs-for-different-experimental-conditions.
The impact of these different update strategies can then be plotted with this:

```lisp
(create-graphs-for-different-experimental-conditions
 :asdf-system "babel-demo"
 :package "babel-demo"
 :experiment-base-class "naming-game"
 :experiment-classes '("ng-1" "ng-2" "ng-3")
 :captions '("no update" "update" "update + lateral inhibition")
 :number-of-interactions 2000
 :number-of-series 10
 :data-recorders '("babel-demo::record-communicative-success"
 "babel-demo::record-average-number-of-words")
 :average-data 't
 :parameters-for-graphic-generators
 '(((:x-label "number of interactions" :y1-label "communicative success"
   :error-bars t :yi-max 1 :yi-min 0 :draw-y1-grid t
   :graphic-type "pdf" :key-location "right bottom"
   :file-name
    (babel-pathname
     :name "success-vs-update-strategy" :type "pdf"
     :directory '("experiments" "babel-demo" "graphs")))))

(:x-label "number of interactions" :y1-label "lexicon-size"
 :error-bars t :yi-min 0 :draw-y1-grid t
 :graphic-type "pdf" :key-location "right bottom"
 :file-name
  (babel-pathname
   :name "lexicon-size-vs-update-strategy" :type "pdf"
   :directory '("experiments" "babel-demo" "graphs")))))
```

The resulting graphs are shown in figure 4.3.

- **:asdf-system**: The same as in `run-parallel-batch` above.
- **:package**: The base class of the different conditions (only needed for creating graph file names).
- **:number-of-interactions**: The experiments to run (a list of strings).
- **:number-of-series**: A graph caption for each of the conditions.
- **:experiment-base-class**: The measures (data recorders) to use. For each measure a separate graph will be created.
- **:average-data**: Determines for each of the measures whether the results are averaged or not.
- **:parameters-for-graphic-generators**: Specifies the appearance of the graphs. Internally, instances of `gnuplot-graphic-generator` are created and everything in `:parameters-for-graphic-generators` is passed to them, so for details see section 3.2.4.3.
Figure 4.4: Examples for graphs create by `create-graphs-for-different-experimental-configurations`.
4.5.3 function create-graphs-for-different-experimental-configurations &key ...

description This is very similar to create-graphs-for-different-experimental-conditions, with the difference that it does not require to create separate classes for each experimental condition. Instead, the same experiment class is run multiple times with different configurations.

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example This example runs the naming-game experiment class 5 times, each time with a different probability for the invention of words:

(defun create-graphs-for-different-experimental-configurations
  (asdf-system "babel-demo"
   :package "babel-demo"
   :experiment-class "naming-game"
   :configurations
     '(((babel-demo::probability-for-word-invention . 1.0))
       ((babel-demo::probability-for-word-invention . 0.5))
       ((babel-demo::probability-for-word-invention . 0.25))
       ((babel-demo::probability-for-word-invention . 0.125))
       ((babel-demo::probability-for-word-invention . 0.05))))
   :captions '("1.0" "0.5" "0.25" "0.125" "0.05")
   :number-of-interactions 2000
   :number-of-series 10
   :data-recorders '("babel-demo::record-communicative-success"
                     "babel-demo::record-average-number-of-words")
   :average-data ’(t t)
   :parameters-for-graphic-generators
     ’((:x-label "number of interactions" :y1-label "communicative success"
       :error-bars t :y1-max 1 :y1-min 0 :draw-y1-grid t
       :graphic-type "pdf" :key-location "right bottom"
       :file-name
         (babel-pathname
          :name "success-vs-invention-probabilities" :type "pdf"
          :directory ’("experiments" "babel-demo" "graphs")))
     (:x-label "number of interactions" :y1-label "lexicon-size"
      :error-bars t :y1-max 1 :y1-min 0 :draw-y1-grid t
      :graphic-type "pdf" :key-location "right bottom"
      :file-name
        (babel-pathname
         :name "lexicon-size-vs-invention-probabilities" :type "pdf"
         :directory ’("experiments" "babel-demo" "graphs")))))

The resulting-graphs are shown in figure 4.4.
The same as in `create-graphs-for-different-experimental-conditions` above.

- **:experiment-class**: The class of the experiment to run with different configurations.
- **:configurations**: Lists of configurations for each run. A configuration is a list of configuration / value pairs and the client processes pass them to the experiment with `set-configuration`.
- **:captions**: A graph caption for each of the configurations.

### 4.5.4 function `create-graphs-for-different-population-sizes` &key ...

- **description**: This function shows the impact of varying population sizes on particular measures. In order to make the different runs comparable, the x-axis does not show the number of interactions, but the number of interactions that each agent played on average. When for example the population size is 10 and the number of series 1000, then each agent will have played 200 games until the end.
Figure 4.5: Examples for graphs create by `create-graphs-for-different-population-sizes`. 
This example runs the `naming-game` experiment class with 6 population sizes:

```lisp
(create-graphs-for-different-population-sizes
 :asdf-system "babel-demo"
 :package "babel-demo"
 :experiment-class "naming-game"
 :population-sizes '(10 50 100 250 500 1000)
 :number-of-interactions-per-agent 1000
 :number-of-series 10
 :data-recorders '("babel-demo::record-communicative-success"
          "babel-demo::record-average-number-of-words")
 :average-data '(t t)
 :parameters-for-graphic-generators
 '((:key-location "bottom right"
    :x-label "number of interactions per agent"
    :y1-label "communicative success" :error-bars t
    :y1-min 0.0 :y1-max 1 :draw-y1-grid t
    :graphic-type "pdf" :colored t
    :file-name
      (babel-pathname
       :name "success-vs-population-size" :type "pdf"
       :directory '("experiments" "babel-demo" "graphs")))
  (:key-location "top right"
   :x-label "number of interactions per agent"
   :y1-label "lexicon size" :error-bars t :y1-min 0
   :y1-max 150 :draw-y1-grid t
   :graphic-type "pdf" :colored t
   :file-name
     (babel-pathname
      :name "lexicon-size-vs-population-size" :type "pdf"
      :directory '("experiments" "babel-demo" "graphs")))
 ))
```

The resulting graphs are shown in figure ??.

- **:asdf-system**
  - See above.

- **:package**

- **:experiment-class**

- **:number-of-series**

- **:data-recorders**

- **:average-data**

- **:parameters-for-graphic-generators**

- **:population-sizes**
  - A list of different population sizes. This will be used in the client processes to do `(set-configuration experiment 'population-size xxx)`, so you will have to create populations depending on `population-size`.

- **:number-of-interactions-per-agent**
  - How many interactions to run per agent. If for example the population size is 1000 and the :number-of-interactions-per-agent 1000, then 500000 interactions will be run by each client process.
5 Learning

Learning is deeply entrenched into the Babel framework. Learning in Babel cannot be only inductive learning since the agents also have to invent or change new items for their (linguistic) inventory to be gradually built up. We cannot assume (like is often done in machine learning algorithms) that there is a pre-given input set from which the agents can learn. In other words we do not assume that there is a teacher. All the input an agent ever gets is the world and output from other agents. This requires a constructivist approach to learning. To meet these requirements we have split up learning into diagnosing and repairing. In section 5.1 we present the definitions for the base classes including diagnostic, problem and repair-strategy. Sections 5.2 and 5.3 present the two instantiations of this base-framework that we have provided by default in Babel. These are the process level learning mechanisms and the agent level learning mechanisms. We use the term learning mechanism to signify both diagnostic and repair-strategy. Section 5.4 shows a detailed example on how to write a diagnostic, with a corresponding problem and repair-strategy.

I suggest for everybody who intends to write an experiment to read the complete chapter carefully.

5.1 Base classes

The classes in this section are abstract base classes of the learning mechanisms. Different levels of learning mechanisms subclass from them and add further semantics. All these classes can be found in the file “learning-mechanisms.lisp” in the experiment-framework.

5.1.1 class diagnostic

| description | The base class for all diagnostics. |
| situations | (learning-situations :type list :reader learning-situations :initform nil :initarg :learning-situations) |

A situation narrows down the point of execution of a diagnostic. The kinds of learning-situations depends on the level the diagnostic is operating on. It is a list of symbols.

5.1.2 monitor event diagnostic-started (diagnostic diagnostic)

| description | Triggered when a diagnostic starts running. |
| diagnostic | The diagnostic that is run. |

5.1.3 class problem
5 Learning

| description | Represents a problem. A problem is created by diagnostics to signal a failure or some inefficiency and contains all the information necessary to deal with the problem. |

| slot issued-after | (issued-after :type symbol
:accessor issued-after
:initform nil
:initarg :issued-after)

This is a symbol representing when this problem was signaled. When created by a process-diagnostic this is the name of the process. |

| slot repaired-by | (repaired-by :type t :accessor repaired-by
:initform nil
:initarg :repaired-by)

This slot is automatically set to the repair-strategy that repaired it. When it’s nil it means it’s still unrepaired. |

5.1.4 monitor event diagnostic-returned-problems (diagnostic diagnostic) (problems list)

| description | Triggered after a diagnostic was run and only if it returned at least one problem. |

| diagnostic | The diagnostic that was run. |

| problem | The list of problems that was returned. |

5.1.5 class repair-strategy

| description | Base class for all repair strategies. Repair strategies are able to deal with a set of problems. |

| slot triggered-by-problems | (triggered-by-problems :type list :reader triggered-by-problems
:initform nil
:initarg :triggered-by-problems)

A list of problems (class names of problems) that the repair strategy might be able to fix. |

| slot learning-situations | (learning-situations :type list :reader learning-situations :initform nil
:initarg situations)

situation narrows down the point of execution of a repair-strategy. The kinds of learning-situations depends on the level the repair-strategy is operating on. It is a list of symbols. |
slot **success-score**  
$(success-score :type number :accessor success-score  
:initform 1.0 :initarg :success)$  

Resembles how successful the repair-strategy is. The higher the better. This will be used to sort when multiple repair-strategies can be triggered at the same time.

5.1.6 **monitor event** **repairing-started**  
$(repair-strategy repair-strategy) (problem problem))$  

<table>
<thead>
<tr>
<th>description</th>
<th>When a repair strategy is called.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>repair-strategy</strong></td>
<td>The repair strategy that is called.</td>
</tr>
<tr>
<td><strong>problem</strong></td>
<td>The problem on which it is called.</td>
</tr>
</tbody>
</table>

5.1.7 **monitor event** **repairing-finished**  
$(repair-strategy repair-strategy) (repaired boolean))$  

<table>
<thead>
<tr>
<th>description</th>
<th>After a repair strategy was run.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>repair-strategy</strong></td>
<td>The repair strategy that was run.</td>
</tr>
<tr>
<td><strong>repaired</strong></td>
<td>Whether it was able to repair or not.</td>
</tr>
</tbody>
</table>

5.1.8 **class** **object-with-learning-mechanisms**  

<table>
<thead>
<tr>
<th>description</th>
<th>A helper class that provides derived classes with learning mechanisms. At the moment of writing the classes that derive from this are an experiment [4.2.1.1], an agent [4.1.2.1] and a task [6.1.1].</th>
</tr>
</thead>
</table>
| slot **diagnostics** | $(diagnostics :type list :accessor diagnostics  
:initarg :diagnostics :initform nil)$  

A list of diagnostics. |
| slot **repair-strategies** | $(repair-strategies :type list :accessor repair-strategies  
:initarg repair-strategies :initform nil)$  

A list of repair strategies. |

5.1.9 **generic function** **add-diagnostic**  
**object diagnostic**  

<table>
<thead>
<tr>
<th>description/default implementation</th>
<th>Adds a diagnostic to <strong>object</strong>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>object</strong></td>
<td>Anything that is derived from <strong>object-with-learning-mechanisms</strong>.</td>
</tr>
<tr>
<td><strong>diagnostic</strong></td>
<td>An instance of a diagnostic. If there is already an diagnostic of the same class as <strong>diagnostic</strong> in <strong>object</strong>, that diagnostic is replaced and you will get a warning.</td>
</tr>
</tbody>
</table>
example  (add-diagnostic *experiment*
              (make-instance 'uncovered-meaning-diagnostic))

5.1.10 generic function delete-diagnostic object diagnostic

description/ default implementation
object       Anything that is derived from object-with-learning-mechanisms.
diagnostic   A diagnostic of object.

5.1.11 generic function add-repair-strategy object repair-strategy

description/ default implementation
object       Anything that is derived from object-with-learning-mechanisms.
repair-strategy An instance of a repair strategy.

5.1.12 generic function delete-repair-strategy object repair-strategy

description/ default implementation
object       Anything that is derived from object-with-learning-mechanisms.
repair-strategy A repair strategy of object.

5.1.13 monitor trace-learning trace-monitor

description Prints information on detected and repaired problems.

5.1.14 monitor trace-learning-verbose trace-monitor

description In addition to the stuff printed by monitor trace-learning, it also prints which learning mechanisms are run and changes of an agent’s inventories (for example when rules are added or modified).

5.2 Process level learning

In Babel one can learn (by default) both at the level of processes (see chapter ?? if you don’t know what processes are) and at the level of an agent. In this section we focus on the process level learning mechanisms.
A process-diagnostic can be run after any given process. It can report a problem if it detects one. After every process there is a check for new problems and the process level repair strategies get a chance to fix them. In case of a successful repair the repaired-by slot of the process get’s set to the repair-strategy and there might be a restart to a previous process. This will become more clear when you get read about the classes and their methods further down. All of this can be found in the file “process-learning-mechanisms.lisp” in tasks-and-processes.

### 5.2.1 class process-diagnostic diagnostic

**description**  
A diagnostic that is triggered after the execution of a process. Examples of possible learning-situations are production, re-entrance, interpretation, production.

**slot**  
(trigger-processes :type list :reader trigger-processes :initform nil)

**trigger-processes**  
The names of processes after which this diagnostic should be triggered.

This means the exact point of execution of a process-diagnostic is a combination of the learning-situations and the trigger-processes. For example if the learning-situations are ’(production) and the trigger-processes are ’(apply-lex-stem) the diagnostic will only be called during production and after the lex-stems were applied.

To run a process-diagnostic one has to implement a diagnose-process method. If you define a process-diagnostic without supplying an implementation for this method an error will be thrown. Diagnose-process should return either one problem, a list of problems or nil. If this is not the case an error will be thrown. In case one or more problems are returned they are automatically added to the problems of the task that is currently running. When nil is returned it means that the diagnostic did not diagnose anything.

### 5.2.2 generic function diagnose-process process-diagnostic task process

**description/ default implementation**  
Diagnose-process is called after running a process and handling it’s process-results. It’s exact call-location depends on the combination of it’s trigger-processes and it’s learning-situations. e.g. If trigger-process is apply-lex-stem and situation is production this method will only be executed after apply-lex-stem during production of the speaker and nowhere else.

**process-diagnostic**  
The diagnostic you want to specialise on.

**task**  
You will need this task for diagnosing a potential problem.

**process**  
A process is just a symbol but it might be necessary if the diagnostic can be triggered after different processes. Since we provide you with the process you know immediatly in which case you are. You can even specialise on it.

### 5.2.3 class task-problem problem
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description A problem is always related to a task. Therefore you should always derive from this and not from the base-class problem.

slot task (task
  :type task
  :initform (error "When creating a task-problem you have to supply a :task")
  :initarg :task
  :accessor task)

The task this problem is about.

5.2.4 class process-repair-strategy repair-strategy

description A process-repair-strategy can be triggered on a problem. Process repair-strategies are checked in between every process. Every process-repair-strategy should have a repair-process method specialised on it. Repair-process can return two values. The first a boolean whether the repair succeeded or not. Second a process (which is a symbol) to which the task must be restarted. If this is nil it will just continue. I would like to stress that one should be very careful in setting the first boolean to true and restarting. Because if the problem during the restart gets signaled again the repair will be triggered again and one potentially finds himself in an infinite loop. So only return true (with a restart) when you are very certain that all necessary modifications have been made so that the problem will not get diagnosed anew.

5.2.5 generic function repair-process repair-strategy problem task process

description/ default implementation In between every process the problems will be checked and if possible a correct repair-process will be executed. It can return two values. The first a boolean whether the repair succeeded or not. Second a process (which is a symbol) to which the task must be restarted. If this is nil it will just continue.

repair-strategy The repair-strategy you want to specialise on.

task The current task. You will probably also need it for repairing.

problem The problem that triggers the repair-strategy. You probably need to specialise on this too. A problem can contain many usefull slots containing information already gathered during diagnosing.

process A process is just a symbol but it might be necessary if the diagnostic can be triggered after different processes. Since we provide you with the process you know immediatly in which case you are. You can even specialise on it.
5.3 Agent level learning

Sometimes it is impossible to diagnose or repair something in between processes. One reason is that at the process level you do not have all the information necessary to perform the diagnosis. For example when you need re-entrance information and compare this to production. Sometimes it is possible to diagnose something after a given process but can only repair it later e.g. after receiving pointing information.

One of the nicest features of the learning framework is that problems are “level-independent”. A problem diagnosed by a process level diagnostic can be repaired by an agent level repair-strategy. This is possible because all the problems from the (best) task get copied to the agent when the task has finished. Actually it runs deeper, there is no direct link between a diagnostic and a repair-strategy. Their connection is only indirect by the use of problems.

We will start by presenting the most important classes. All the information presented here can be found in “agent-learning-mechanisms” in experiment-framework.

5.3.1 class agent-diagnostic diagnostic

description A diagnostic that is triggered after run-agent.

For every agent-diagnostic one has to supply a diagnose-agent method.

5.3.2 generic function diagnose-agent diagnostic agent-interaction-point agent world

description/ default After run-agent diagnose-agent will be called for every agent-diagnostic. They have to return either one problem, a list of problems or nil. The problems will be pushed onto the problems of the agent automatically.

implementation diagnostic The diagnostic you want to specialise on.

agent-interaction-point is a more specific name for a learning situation at the agent level. It is a symbol and can be used to specialise or just to check what the interaction-point is.

agent The agent that is currently running.

world This is one of the major differences with a process-diagnostic that one has access to the world at this level.

5.3.3 class agent-repair-strategy repair-strategy

description These repair strategies are executed after run-agent. They try to repair problems in the agent, which could also be problems created by lower-level diagnostics.

Every agent-repair-strategy should supply a repair-agent method. A repair-agent-method can return two values. The first a boolean whether the repair was successful or not. Second can be anything which is guaranteed to be put into the “rerun-data” slot of the agent. The second value
only matters when the first is non-nil and consists of rerun-data. When it is not nil it signifies a restart of run-agent. This second value will also be stored automatically in the “rerun-data” slot of the agent. This allows one to change the behaviour during a rerun. For example one could skip conceptualisation.

5.3.4 generic function repair-agent repair-strategy agent-interaction-point problem agent world

description/ default implementation

repair-agent is called after run-agent. It might however also repair problems created by lower-level diagnostics. It can return two values. The first one a boolean signifying whether the repair was successful. The second rerun-data that is automatically stored in the rerun-data slot of the agent. When the rerun-data is non-nil a restart will be initiated.”

repair-strategy The repair-strategy you want to specialise on.
agent-interaction-point This is a more specific name for a learning situation at the agent level.
problem The problem that triggers the repair-strategy. You probably need to specialise on this too. A problem can contain many usefull slots containing information already gathered during diagnosing.
agent You have access to the agent during repairing.
world You have access to the world during repairing.

5.3.5 class rerun-data

description An empty abstract class that can be used to derive from when creating objects to return as second value in repair-agent. Rerun-data-with-restored-task which is used in the language-game templates is derived from this.

5.3.6 class rerun-data-with-restored-task rerun-data

slot (trigger-processes :type list :reader trigger-processes :initform nil)

trigger-processes The names of processes after which this diagnostic should be triggered.

5.4 Detailed example

We will start with an example for writing process level learning mechanisms. If you are not yet acquainted with the cookie-baking example in section 6.3 from chapter ?? then I suggest you read that first because the current example builds further on that one.

For clarity reasons, here is what we had so far.

(defclass cookie-baking-agent (agent-with-tasks)
(:documentation "An agent capable of making delicious cookies.")

(defmethod initialize-instance :after ((agent cookie-baking-agent) &key) 
  (add-data-field agent 'available-ingredients nil))

(defclass simple-cookie-baking-task (task)
  ()
  (:documentation "An implementation of a task for baking simple cookies.")

(defmethod initialize-instance :around ((task simple-cookie-baking-task) &key &allow-other-keys) 
  (call-next-method)

  (add-data-field task 'used-ingredients nil)
  (add-data-field task 'missing-ingredients nil)
  (add-data-field task 'cookies nil)

  (add-process task 'find-all-ingredients nil)
  (add-process task 'make-cookies '(find-all-ingredients))
  (add-process task 'bake-cookies '(make-cookies)))

(defmethod run-process ((task simple-cookie-baking-task) (process (eql 'find-all-ingredients)))
  (if (subsetp '(chocolate flour) (get-data task 'available-ingredients))
    (list (make-process-result :succeeded t :confidence 1.0
                              :data (list (cons 'ingredients (chocolate flour))))))
    (list (make-process-result :succeeded nil :confidence 0.0
                              :data (list
                                    (cons 'ingredients
                                          (intersection '(chocolate flour)
                                                        (get-data task 'available-ingredients))))))))

(defmethod run-process ((task simple-cookie-baking-task) (process (eql 'make-cookies)))
  ...
  (list (make-process-result ...)))

(defmethod run-process ((task simple-cookie-baking-task) (process (eql 'bake-cookies)))
  ...
  (list (make-process-result ...)))

(defmethod goal-achieved ((task simple-cookie-baking-task)) 
  (and (find 'bake-cookies (finished-processes task))
       (succeeded (get-process-result task 'bake-cookies))))

What would happen if an agent runs out of some ingredients. This would mean that every cookie-
baking task would fail since find-all-ingredients would fail.

To solve this issue we define a process-diagnostic that is able to detect that ingredients are missing.

(defclass detect-missing-ingredients (process-diagnostic)
(:documentation "After running find-all-ingredients this
diagnostics checks whether there were ingredients missing.")

(defmethod initialize-instance :after (((diagnostic detect-missing-ingredients) &key)
    (setf (slot-value diagnostic 'trigger-processes) '(find-all-ingredients))
    (setf (slot-value diagnostic 'learning-situations) '(baking)))

Note the after method that sets the learning-situations and at this point more important the
trigger-processes. We also create a problem that this diagnostic can create in case of a shortage of
ingredients.

(defclass missing-ingredients-problem (task-problem)
  (:documentation "This problem is created when there are missing ingredients.")

It has one slot that can be used to store the missing ingredients. In this way the repair-strategy
does not have to look for them again but can just access them from this problem.

Now it’s time to supply the diagnose-agent method which will do the diagnosing.

(defmethod diagnose-process (((diagnostic detect-missing-ingredients)
    (task task) (process symbol))
  (let ((process-result (get-process-result task 'find-all-ingredients)))
    (when (and (not (pr-succeeded process-result))
      (field? (pr-data process-result) 'missing-ingredients))
      (make-instance 'missing-ingredients-problem
        :missing-ingredients (get-data process-result 'missing-ingredients)
        :task task))))

This is all that is necessary for creating a diagnostic that will successfully diagnose missing ingre-
dients. Of course we need to supply a repair-strategy that can handle this problem by buying the
missing ingredients.

(defclass buy-missing-ingredients (process-repair-strategy)
  ()
  (:documentation "This repair strategy will add some more
ingredients to the available ingredients.")

(defmethod initialize-instance
  :after (((repair-strategy buy-missing-ingredients) &key)
    (setf (slot-value repair-strategy 'triggered-by-problems) '(missing-ingredients-problem))
    (setf (slot-value repair-strategy 'learning-situations) '(baking)))

The after method makes sure that the repair-strategy knows which problems it might be able to
repair. It has the same learning-situations so will trigger right after the diagnostic. The repair-agent
method can be implemented as follows:

(defmethod repair-process ((rs buy-missing-ingredients)
(problem missing-ingredients-problem) (task task)
  (process symbol))
(loop for (ingredient amount) in (get-data (agent-data task) 'available-ingredients)
    when (find ingredient (missing-ingredients problem) :test #'equal)
    do (ns subst (list ingredient 5))
  (list ingredient 0)
  (get-data (agent-data task) 'available-ingredients)
  :test #'tree-equal))
(when (every #'(lambda (item) (> (second item) 0)))
  (get-data (agent-data task) 'available-ingredients))
  (values t 'find-all-ingredients)))

This will search for ingredients for which we have zero in stock and put 5 new there. It will restart at the beginning of find-all-ingredients but only when it is certain that it has indeed supplied all the necessary ingredients.
6 Tasks and Processes

Most of this chapter is not needed when writing experiments. When using the language game templates you will only get confronted with tasks when writing learning mechanisms.

For those that would like to read the minimum and are not interested in writing their own tasks we advise section 6.1.1.1 and when you’re interested in writing process learning mechanisms it is strongly advised to read chapter 5 carefully and since you will be accessing information about the processes it is also recommended to read section 6.2.

Section 6.3 clearly shows an example of how to create a task and knowing how to write your own will most certainly help you in understanding the default tasks.

For those who are interested how tasks and processes are run behind the scenes there is section 6.1.2. If you are writing advanced learning mechanisms it might also be a good read.

6.1 Tasks, task-processors and task-results

Tasks are used for maintaining and running processes. They are the primary interface to tasks and processes. From the moment you want more control over your experiments then the default behaviour you will have to deal with tasks. In section 6.1.1.1 class task is explained in full detail.

6.1.1 Task

6.1.1.1 class task object-with-learning-mechanisms

description A “task” inherits from object-with-learning-mechanisms. Besides the slots it inherits from its superclasses it contains some new slots that are specific to a task.

slot (id :type symbol :reader id)
A symbol that is generated automatically during instantiation by incrementing the id-counter and prepending it with ’TASK. Therefore id’s are of form “TASK-X”.

slot (data :type blackboard :accessor data :initarg :data)
Data that is local to the task and exchanged between processes.

slot (agent-data :type blackboard :accessor agent-data :initarg :agent-data)
(A copy of) the persistent data (inventories) of the agent.
slot (processes :type list :initform nil :reader processes)
An alist of processes and their dependencies that are used by this task. A list of conses (a . (b c)): a depends on b and c.

slot (finished-processes :type list :initform nil :accessor finished-processes)
The processes that have been run.

slot (process-results :type list :initform nil :accessor process-results)
An alist of all finished processes and their process-result. When a process finished it returns a process-result. This result is always (irrespective of it being successful or not) added to the process-results.

slot (problems :type list :initform nil :initarg :problems :accessor problems)
All the problems that were reported by diagnostics operating on a task level or lower. (e.g. the process-diagnostics)

slot (data-states :type list :initform nil :initarg :data-states :accessor data-states)
We keep a copy of the data-slot at the beginning of every process. This allows for very easy, fast and non-ambiguous restoring of a task. Although it comes at some copying cost during task execution. It is an alist of (process . data).

slot (agent :type list :initform nil :initarg :agent :accessor agent)
A pointer to the agent which created this task (if applicable). Added this slot for monitoring purposes only.

slot (configuration :type configuration :initarg :configuration :accessor configuration)
For configuring the task.

First we present the generic functions that you will probably need when creating your own task or writing learning mechanisms.

6.1.1.2 generic function get-process-result task process

description/ default implementation
Returns the process-result for the given process. It errors when it cannot find a process-result for the given process.

6.1.1.3 generic function run-process task process

description/ default implementation
This is the method that has to be implemented for every process. It is in a sense what defines the process. It should return a list of process-results. Even when a process fails it should return a list containing one process-result.
6.1.1.4 *generic function* **goal-achieved** task

**description/ default implementation**
Returns t if the goal of a task was achieved. It is a very important method because a task can only be successful if it passes this test. When it does it also completely stops the running of any other processes from the task because it has achieved what it needed to.

6.1.1.5 *generic function* **finished-processes** task

**description/ default implementation**
Returns a list of all processes that have been run irrespective of them being successful.

6.1.1.6 *generic function* **add-process** task process dependencies

**description/ default implementation**
Adds a process and it’s dependencies to a task.

6.1.1.7 *generic function* **delete-process** task process

**description/ default implementation**
Deletes a process and it’s dependencies from a task.

6.1.1.8 *generic function* **run-task** task

**description/ default implementation**
Runs the given task. It returns a task-result-collection since running a task could spawn many new tasks in case of ambiguity.

The following generic functions are more internal to the execution of tasks and processes and you will most probably not need them unless you are interested in changing how a task is run.

6.1.1.9 *generic function* **get-all-process-dependencies** task process optional result

**description/ default implementation**
Returns a list of all the processes that *have to be finished before* this process can be run. This is a recursive (and deeper) variant of get-process-depencies.

6.1.1.10 *generic function* **get-all-dependent-processes** task process optional result

**description/ default implementation**
Returns a list of all processes that *cannot* be run before the given process is run. So all the processes that are directly or indirectly dependent on the given process.

6.1.1.11 *generic function* **dependencies-solved?** task process

**description/ default implementation**
Returns true if all the dependencies of the given process are solved.
6.1.1.12 **generic function** `get-processes-without-dependencies` *task*

description/ default implementation Returns a list of processes without their dependencies. This is just a list of all the processes the task knows.

6.1.1.13 **generic function** `get-process-dependencies` *task process*

description/ default implementation Returns a list of processes on which the given process depends. The list contains only the direct dependencies. e.g. If 'a' depends on 'b' and 'b' depends on 'c' and you ask get-process-dependencies for 'a' it will only give you 'b' and not 'c'. If you want the complete list of dependencies use get-all-process-dependencies.

6.1.1.14 **generic function** `add-process-result` *task process process-result*

description/ default implementation Add the process-result to the process-results of the object.

### 6.1.2 Behind the scenes: Running of a Task

Running all the processes in a task requires a lot of bookkeeping. For example one needs to keep track of all the processes that have been run, after every process check whether dependencies of some processes have been met and queue them so they can be run next. Since we did not want to clutter the class task, we created a new structure `task-processor` that contains one task, namely the task that is being run and has some extra slots such as a process-queue for bookkeeping. Normally you should never have to create a task-processor yourself. This is all done automatically behind the scenes. Moreover chances are very small you will ever interface with a task-processor since when a task has finished a task-result (see section 6.1.2.4) is created and the task-processor gets collected in the garbage.

#### 6.1.2.1 **structure** `task-processor` *node*

description A task-processor contains a task and other information needed for running the processes in this task.

slot (task :type task :accessor tp-task :initarg :task :initform (error "Please provide a task when creating a task-processor."))

The task this task-processor task is processing.
6 Tasks and Processes

slot (confidence :type float :accessor tp-confidence :initarg :confidence :initform 0.0)

This is used during running tasks for determining which should be run next. So tasks are run by priority on their confidence. And also in the end the best-task is the one with the highest confidence. The confidence of a task is a function of the confidences of the processes it has run.


The process-queue is used for keeping track of the processes when running them.

6.1.2.2 *generic function* restart-task task-processor process

description/ default Restart a task at a specific process. Restores the process-queue of the task-processor and rewrites previous process results to the black board.

implementation

6.1.2.3 *generic function* run-processes task-processor

description/ default Try running all processes of the task inside the task-processor.

implementation

There are three different possibilities for a task to stop.

1. First (goal-achieved task) could return true. When this is the case the task has achieved it’s goal and stops it’s execution.

2. Second when a task has no more processes to run (because it has run them all, or because some dependencies are not met) and the goal has not been achieved yet the task simply fails.

3. Third the task could also “split” into multiple new tasks. This only happens when run-process returns more then one process-result. When this is the case the original task also stops and the newly created tasks take over. In a sense the task not really stops, it just hands over responsibility to it’s children.

In the first two of these cases an object of structure “task-result” is created. Normally you never have to create a task-result yourself. You will however get in contact with task-results when writing learning mechanisms. In section 6.1.2.4 you find all the details regarding this class.

6.1.2.4 *structure* task-result node

description A task-result is created when a task has finished running. It contains the finished task and some extra slots to indicate whether it succeeded or not and a confidence. This means it has a contains-a relation with the task and not a is-a relation. It derives from node which means it can be used in a tree structure.
slot (task :type task :initform (error "Please provide a task when creating a task-result.")
    :initarg :task :accessor tr-task)

This is the task the task-result is about. Since you only create a task-result when the task has finished you have to immediately supply the task via the :initarg.

slot (confidence :type float :initarg :confidence :accessor tr-confidence
    :initform (error "Please provide a confidence value when creating a task-result"))

A value between 0 and 1. 1 meaning that you are very confident. In most cases this will be a function of the process-results of the task.

slot (succeeded :type boolean :accessor tr-succeeded :initarg :succeeded
    :initform (error "Please provide a boolean value for succeeded when creating a task-result"))

Indicates whether the goal of the task was achieved.

Some generic functions from section 6.1.1.1 are also specialised for a task-processor and a task-result. The call is just passed to task contained in the task-processor or task-result. These are:

- id
- processes
- process-results
- finished-processes

Since a task can split into multiple new tasks and these tasks can split again it is obvious that the running of one task cannot always return one task-result. It might be many different task-results, some of them succeeded others failed. We have captured this in a new structure named task-result-collection. It includes structure mtree which means that is also a tree. When writing learning mechanisms you will most probably have to interface with this class very often.

6.1.2.5 structure task-result-collection mtree

description Contains task-results and task-processors structured as a tree. When running a task it is an instance of task-result-collection that is returned. In the most simple case (when there is no ambiguity) this structure will only contain one task-result. However when ambiguous tasks are run it will be a far more elaborate structure with different task-results.

slot (succeeded-task-results :type list :accessor succeeded-task-results
    :initform nil)

All succeeded task-results. In many cases this will just contain one element.

slot (failed-task-results :type list :accessor failed-task-results
    :initform nil)

All failed task-results.
6.1.2.6  **generic function** **best-task-result** task-result-collection

description/ default  Returns task-result with the highest confidence. It first tries searching succeeded-task-results and if this is empty it tries failed-task-results.

implementation

6.1.2.7  **generic function** **best-task** task-result-collection

description/ default  Returns the task inside the task-result with the highest confidence. It first tries searching succeeded-task-results and if this is empty it tries failed-task-results.

implementation

To conclude this section we present a simplified and incomplete version of how a task is run:

(defmethod run-task ((task task))
  (let ((task-result-collection (make-task-result-collection))
          (task-queue (make-instance 'queue))
          active-task-processor)
    (enqueue-by-priority task-queue (make-instance 'task-processor :task task) #'tp-confidence)
    (loop until (empty-queue? task-queue)
      do
        (setf active-task-processor (pop-front task-queue))
        (solve-process-dependencies active-task-processor)
        (cond ((goal-achieved (task active-task-processor))
               ;; the current task succeeded
               (add (make-task-result :task (tp-task active-task-processor)
                                :succeeded t)
                    task-result-collection))
               ((not (empty-queue? (tp-process-queue active-task-processor)))
                ;; there still are processes to run
                (let ((new-tasks (run-processes active-task-processor)))
                  (enqueue-by-priority task-queue new-tasks #'tp-confidence)))
               (t ;; the current task failed
                (add (make-task-result :task (tp-task active-task-processor)
                                :succeeded nil)
                    task-result-collection))))
  task-result-collection))

6.2  Processes and Process-results

Processes themselves are not modelled as classes since the only thing that defines them is what they do. A process is just a symbol like 'render or 'apply-con-rules but every such symbol should also have a run-process method that specializes on that symbol with an eql statement (also see 6.3 for an example). Since processes are not modelled they use the task they are part of as a blackboard to write their output data. When run-process finishes the data from the process-result is written to the task and the process-result itself is also fully stored in the task for in case one would like to investigate it for learning.

When a process is running (so inside the run-process of that process) three different scenario's are
possible.

1. First everything goes well and the run-process just returns a list containing one process-result with it’s succeeded-slot set to true.

2. Second something went wrong and the process cannot be run successfully. In the cookie baking example it could be that you run out of ingredients. In this case one returns also a list containing one process-result but with succeeded-slot set to nil.

3. Third it could be that there is some kind of ambiguity. e.g. The recipe states that one should add sugar but you don’t know whether it’s brown or white sugar. In this case run-process should return a list process-results with a process-result for every possibility.

A process-result therefore plays a very important role not only in running the task but also when diagnosing or repairing you will interface with the process-results quite often. All process-results are remembered in the slot process-results of the task.

6.2.1 structure process-result

description The output of the execution of a process.

slot (data :accessor pr-data :type list :initarg :data :initform nil)

The data you wish to return to the task. It’s an alist containig pairs of (datafield . data).

slot (confidence :type float :accessor pr-confidence :initarg :confidence :initform 0.0)

How confident the process is of this result.

slot (succeeded :type boolean :accessor pr-succeeded :initarg :succeeded :initform nil)

Whether depending processes should be triggered.

6.2.2 generic function handle-process-result task-processor process process-result

description/ default implementation Checks a process-result and writes all necessary changes to the task-processor (including the task it contains).

6.2.3 generic function handle-process-results task-processor process list

description/ default implementation Handles a list of process-results. This may change the task-processor but it may also spawn new tasks.

6.3 Implementing your own task

Implementing your own task with it’s own processes is very easy.
Assume you wish to create a task for baking cookies. This task contains three processes:

1. find-all-ingredients
2. make-cookies
3. bake-cookies

Although this is not entirely necessary we first create an agent because it makes more sense.

(defclass cookie-baking-agent (agent-with-tasks)
  ()
  (:documentation "An agent capable of making delicious cookies."

(defmethod initialize-instance :after ((agent cookie-baking-agent) &key)
  (add-data-field agent 'available-ingredients nil))

Now we are ready to create a new class that derives from task or a subclass of task.

(defclass simple-cookie-baking-task (task)
  ()
  (:documentation "An implementation of a task for baking simple cookies."

Remember that a task already derives from object-with-learning-mechanisms. So although this new task looks empty it is not. The next step is to let the task know about its processes and their dependencies. It is obvious that one cannot bake cookies before one has made the cookies and one cannot make cookies before one has found all necessary ingredients. So we have a linear dependency between the three processes. We do this as follows:

(defmethod initialize-instance :around ((task simple-cookie-baking-task) &key &allow-other-keys)
  (call-next-method)
  (add-data-field task 'used-ingredients nil)
  (add-data-field task 'missing-ingredients nil)
  (add-data-field task 'cookies nil)
  (add-process task 'find-all-ingredients nil)
  (add-process task 'make-cookies '(find-all-ingredients))
  (add-process task 'bake-cookies '(make-cookies)))

The next thing is to implement run-process methods for all three processes. The most important thing to note is that they specialize on process with eql and that they always return a list of process-results.

(defmethod run-process ((task simple-cookie-baking-task)
  (process (eql 'find-all-ingredients))
  (if (subsetp '(chocolate flour) (get-data task 'available-ingredients))
    (list (make-process-result :succeeded t :confidence 1.0
     :data (list (cons 'ingredients (chocolate flour))))))
  (list (make-process-result :succeeded nil :confidence 0.0
     :data (list (cons 'ingredients
     (intersection '(chocolate flour)
     (get-data task 'available-ingredients))))))))
There is only one thing left to do now, which is to provide a test that allows the task to know it has achieved its goal. This is done by implementing the goal-achieved method.

(defmethod goal-achieved ((task simple-cookie-baking-task))
  (and (find 'bake-cookies (finished-processes task))
       (succeeded (get-process-result task 'bake-cookies)))))

A fully working implementation can be found in the file simple-cookie-baking-task.lisp which can be found under experiment cookie-experiment in folder experiments.

6.4 Process Learning Mechanisms

Since learning is crucially important we have dedicated a chapter to accommodate all there is to know about learning in the Babel framework. We refer you to chapter 5. In that chapter the above example will also be further expanded with learning mechanisms.
7 Fluid Construction Grammar: Syntax and Semantics

7.1 Introduction

Fluid Construction Grammar’s (FCG) linguistic perspective is in the general line of cognitive linguistics and construction grammar (Goldberg, 1995; Langacker, 2000) and like many other contemporary theories it is feature structure- and unification-based. It is currently the only computational construction grammar formalism that can handle both parsing and production using the same set of constructions rather than using separate generation and parsing procedures as is done in other formalisms. So far, FCG has mainly been applied in research on the emergence and evolution of grammatical phenomena (van Trijp, 2008). This document will detail the syntax and semantics required for writing FCG constructions of varying complexity.

7.2 Syntax and Semantics of FCG

The core data structure in FCG is a Coupled Feature Structure (CFS). As the name implies this is a coupling of two feature structures divided by <-->.

These two feature structures are also referred to as left-pole and right-pole and in general (but not necessarily) the left-pole contains the semantics of the structure, the right pole the syntax.

A Feature Structure (FS) is an unordered list of units and a unit is a list starting with a name (which has to be unique in the feature structure) followed by the actual features. A list encloses its elements within parentheses, thus a list of the elements a b and c is written as (a b c). A list can also include sub-lists as for instance the list (e f) instead of the element c which results in the list (a b (e f)).

A feature then is a list starting with a name (which has to be unique in the unit, not in the feature structure) followed by its value which can be any sort of (nested) list structure. The template for a coupled feature structure looks like this:

---

1 The interested reader is pointed to www.fcg-net.org to find links to our publications and more information on FCG.
2 For linguists it might be helpful to think of units as constituents.
3 There is one feature, the referent feature, where the value should not be a list but can be a single symbol. But this is an exception to the rule.
Fluid Construction Grammar: Syntax and Semantics

Coupled Feature Structure

- ((unit-1-name
  (feature-name-1 values) // values should be a list
  (feature-name-2 values)) // unique feature-names in the unit
- (unit-2-name // unique unit-names in the FS
  (feature-name-2 values) // non unique feature-names in the FS
  (feature-name-3 values)))

Note that a unit cannot contain another unit (i.e. they cannot be nested) and thus you cannot in this way build a tree-like feature structure. Instead in FCG a tree structure is built by using a special subunits feature of which the value is a list of unit-names as shown below.

((unit-1
  (subunits (unit-2 unit-3)))
  (unit-2
    (subunits (unit-4)))
  (unit-3)
  (unit-4))

(a) FS in list representation

Language processing in FCG always starts from an initial coupled feature structure consisting of one unit at both sides containing either only meaning (in production) or only form (in parsing). This CFS is then gradually modified by applying a sequence of FCG constructions. These constructions are also coupled feature structures but they can contain variables and special FCG operators that guide the unification process. An FCG variable is represented as a symbol that starts with a question mark. During unification it can be bound to a symbol, a list or another variable, but of course only to one value (check the examples).

Unification Examples

- (unify '(a b (c)) '(a b (c))) // unifies (both lists are equal)
- (unify '(a ?x c) '(a b c)) // unifies and binds variable ?x to b
- (unify '((a (?z)) ?z) // won’t unify because ?z
  '((a (b)) c)) // should be bound both to b and c
- (unify '(a b) '(b a)) // won’t unify because the order differs
- (unify '(a b c) '(a b)) // won’t unify because of c

FCG Special Operators

The FCG special operators guide the unification process by making it either more flexible or stricter. This section gives an overview of the most important ones. These operators are normally put at the beginning of a list and affect the values of that list.
Remark that unification in FCG never adds elements, except when binding variables and thus works differently than HPSG unification [ref]. Adding elements is done by another operation called merge. Just like unification, merging requires two feature structures of which only one can contain special operators. We call the feature structure containing the special operators the pattern and the other one the source. The merger will look for any extension of the source so that it would unify with the pattern.

FCG-Merge Examples

<table>
<thead>
<tr>
<th>Operation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(fcg-merge 'a 'a)</td>
<td>returns 'a</td>
</tr>
<tr>
<td>(fcg-merge '(a) '(a))</td>
<td>returns '(a)</td>
</tr>
<tr>
<td>(fcg-merge '(a) '(a b))</td>
<td>does not merge</td>
</tr>
<tr>
<td>(fcg-merge '(== a) '(a b))</td>
<td>returns '(a b)</td>
</tr>
<tr>
<td>(fcg-merge '(a b) '(a))</td>
<td>returns '(a b)</td>
</tr>
<tr>
<td>(fcg-merge '(==0 a) '(b))</td>
<td>returns '(b)</td>
</tr>
</tbody>
</table>

Merging can also return multiple hypotheses, for example:

```
(fcg-merge '(== ?x a) '(a b c)) returns '(a b c) with ?x bound to either b or c.
```

Before we continue with more advanced ways to alter the feature structure there is one last key idea crucial to the understanding of grammatical constructions in FCG. This is the idea of linking through variable equalities. Both unification and merging are capable of making two distinct variables refer to the same binding. We call this a variable equality.

FCG constructions are thus patterns and the feature structures they apply on the source.

### Operator Definitions

#### Includes Operator (==)

**Functionality:** The includes operator allows the list to be a sub-list of the other list and the ordering doesn’t matter.

**Example:** The last two examples from above will work by adding the includes operator.

```lisp
(unify '(== a b) '(b a))
(unify '(== b a) '(a b c))
```

#### Includes Uniquely Operator (==1)

**Functionality:** The includes uniquely operator is like the includes operator but doesn’t allow elements from the list to appear more than once in the other list. If the element is a list it only checks the first element of this list.

**Example:**

```lisp
(unify '(==1 a b) '(a a b)) // won’t unify although == would
(unify '(==1 (a)) '((a) (a b))) // won’t unify
```

#### Includes Not Operator (==0)

**Functionality:** The Includes Not operator essentially disallows the elements that follow to appear in the other list. Even if one of them appears, it is enough to block the unification (also the ordering doesn’t matter).

**Example:**

```lisp
(unify '(==0 a b c) '(x)) // unifies
(unify '(==0 b a c) '(a)) // does not unify
```

#### Permutation Operator (==p)

**Functionality:** The permutation operator allows the other list to be a permutation of the list (i.e. the order doesn’t matter).

**Example:**

```lisp
(unify '(==p ?x b) '(b a))
(unify '(==p c a) '(c b a)) // This won’t unify, although == would
```

The above extensions allow us to write FCG constructions such as the one shown in figure 7.1.
Remark that unification in FCG never adds elements, except when binding variables and thus works differently than HPSG unification (Pollard, 1989). Adding elements is done by another operation called *merge*. Just like unification, merging requires two feature structures of which only one can contain special operators. We call the feature structure containing the special operators the *pattern* and the other one the *source*.[4] The merger will look for any extension of the source so that it would unify with the pattern. In the examples below the pattern is the first parameter, the source the second.

### FCG-Merge Examples

- `(fcg-merge 'a 'a)` // returns 'a
- `(fcg-merge '(a) '(a))` // returns '(a)
- `(fcg-merge '(a) '(a b))` // does not merge
- `(fcg-merge '(== a) '(a b))` // returns '(a b)
- `(fcg-merge '(a b) '(a))` // returns '(a b)
- `(fcg-merge '(==0 a) '(b))` // returns '(b)

Merging can also return multiple hypotheses, for example:

- `(fcg-merge '(== ?x a) '(a b c))`

returns '(a b c) with ?x bound to either b or c.

Before we continue with more advanced ways to alter the feature structure there is one last key idea crucial to the understanding of grammatical constructions in FCG. This is the idea of *linking through variable equalities* (see (Steels et al., 2005)). As noted earlier one variable cannot be bound to multiple values but multiple variables can be bound to the same value (which can be a variable itself), we call this a variable equality.

### 7.2.1 Modification of Units and Moving Information between Units

Although we can now modify structures by merging in new information this is not powerful enough to build the complex constituent structures needed for processing natural language. In fact there are three important operations we currently cannot achieve:

---

4 FCG constructions are thus patterns and the feature structures they apply on the source.
1. We are unable to create new units.

2. We cannot relocate existing (or new) units in the tree.

3. We cannot move features from one unit to another.

In what follows we will show how we have solved these problems in FCG through a special tree manipulation operator called the J-operator (De Beule and Steels, 2005).

The J-operator is specified inside the feature structure itself and resides at the same level as the units, which is why we refer to the declarations of these operations as J-units. Such a J-unit doesn’t however specify a unit at all, but instead specifies operations on a unit. To distinguish it clearly from “normal” units a J-unit does not start with a symbol (the unit-name) but instead with a list starting with the symbol J.

A J-unit specifies operations for only one unit, called the focus unit. Of course a feature structure can contain multiple J-units allowing operations on multiple units. The focus unit therefore is the only parameter you are required to supply.

```
((?top
  (form ((string ?top "big")))
  ((J ?new-unit)
    (syn-cat ((pos adjective)))))
```

The above feature structure consists of only one “real” unit ?top and one J-unit. When merged it will create a new unit ?new-unit containing the syntactic category adjective. It’s that easy to create new units and as shown in the example, the body of a J-unit (i.e. the part after the initial list) resembles that of a regular unit in that it can contain feature value pairs.

Although we can now create new units we would still like to specify where it should be located in the feature structure tree. This is, we would like to specify its parent unit and optionally even child units. This can be done by two optional parameters following the focus unit, first specifying the parent and then a list of children as shown in figure 7.2.

In the examples so far the focus unit has always been a reference to a new unit. The focus unit however, can refer to an existing unit as well. It will then not create a new unit but operate on the referred unit.

From the three missing operations presented above we have now addressed the first two. All that remains is the moving of features from one unit to another (existing or new) unit. To move something from A to B you need a way to mark the thing you wish to move and whereto. Marking what feature value pair you wish to move is done by the tag-operator which allows you to bind a feature-value pair to a variable. It has the following syntax:

```
(tag ?tag-name (feature value))
```

You can then simply put the tag variable (i.e. ?tag-name) in the body of a J-unit to mark where the feature value pair should be moved to. It works like cut and paste, you cut by the tag-operator and paste by placing the tag-variable at the desired location in a J-unit. This means the body of a J-unit also allows these tag-variables to reside there next to feature value pairs. You cannot refer

---

5 This could be done by merging, but not for complex trees and this would also cause problems with the bidirectionality of FCG.
7 Fluid Construction Grammar: Syntax and Semantics

{(top
  (syn-subunits (unit-1 unit-2 unit-3))
  (form ((meets unit-1 unit-2)
          (meets unit-2 unit-3)))))

(a) Syntactic Feature Structure

{(unit-1
  (form ((string unit-1 "FCG'")))
  (syn-cat (ref-expression)))

(b) Syntactic pole of an FCG construction

{(unit-2
  (form ((meets unit-4 unit-5)))
  (syn-cat ((pos verb)))
  (syn-subunits (unit-4 unit-5)))

(c)

Figure 7.2: Transformation of a feature structure by a J-unit.

to a tag-variable in regular units. An example is shown in figure 7.3 where a very small initial
feature structure containing only one unit with some meaning is transformed into a a new feature
structure containing two units and where the tagged meaning is moved from one to the other.

To conclude the syntax of a J-unit looks as follows:

{(J ?new ?top (?created ?create ?creator))

with focus the only required parameter being a new variable or one of an existing unit. Parent
should be a variable referring to an existing unit and children a list of existing unit variables. Body
can contain tag-variables next to regular feature value pairs.
7.3 Language Processing in FCG

So far we have been concentrating on unification and merging of single feature structures. We will now focus on coupled feature structure and how they are processed in bi-directional language processing.

Fluid Construction Grammar supports both production (generation in HPSG terminology) and parsing using the same set of constructions. Both start with an initial coupled feature structure that contains either only meaning (in production) or form (in parsing). This coupled feature structure is the key data structure of the language processing. It is this structure that will be modified by applicable constructions finally resulting in a much larger feature structure containing the inferred form and meaning. A high level view of such processing shown in figure 7.4.

As is clear from figure 7.4 applying a construction consists of at least two phases, a unification phase and a merge phase. As explained in section 7.2 unification is quite strict and can thus be seen as a conditional for the construction to apply. We do not both left and right pole of the coupled feature structure but only the left pole in production and the right-pole in parsing. When unification of the required pole is successful both poles of the construction are merged with the central coupled feature structure.

---

We take J operations to be part of merging.
Figure 7.4: A schematic high level depiction of language processing in FCG. From left to right you start with an initial coupled feature structure (cfs). Every construction tries to unify with the cfs and those that can, can merge with the cfs thereby altering it and potentially allow other constructions to unify. This process is repeated until no constructions can apply any longer.
8 Test Framework

We supply a home-made, light weight unit testing framework that makes use of the powerful conditions system in lisp and the monitoring system from Babel.

In this chapter we will not describe its inner working but only its outward functionality. All of the code can be found in tests/test-framework.lisp.

8.1 Writing tests

Instead of using defun of defmethod when writing unit tests you use deftest. It behaves just like a defun but is surrounded by error-capturing and reporting functionality. In a deftest you can do whatever you would normally do in a defun with the addition of test-error, test-ok and test-assert which you can wrap around other calls.

8.1.1 macro test-error expression

description test-error should be used for testing that errors you expect to be thrown, are indeed thrown. When wrapping an expression in test-error it will expect an error to be thrown. It will capture any error that is thrown, print a dot and continue. If however no error is thrown, it throws an error itself.

8.1.2 macro test-ok expression

description When wrapping an expression in test-ok you expect that no error will be thrown. If an error should be thrown it will be captures and it’s message will be printed later on. Furthermore an “x” will be printed instead of a dot.

8.1.3 macro test-assert expression

description When wrapping an expression in test-assert you expect the expression to not throw an error and return not nil. If however nil is returned this will be printed later on. If an error should be thrown this will also be reported.

The nice thing about these three macros is that they give informative feedback when things go wrong and it will continue its processing even if errors are thrown. If all goes well only dots will be printed for every call to one of those macros.
8.2 Example

(defun func-that-throws-an-error ()
 (error "foo bar"))
(defun func-that-throws-no-error ()
 t)

deftest test-1 () ;; these are good tests
 (test-assert (and (equal 2 (+ 1 1))
 (eql (* 2 5) 10)))
 (test-ok (find 1 '(1 2 3)))
 (test-error (func-that-throws-an-error))
 ;; the next ones go wrong, but indeed the code keeps running
 (test-assert (equal 1 2))
 (test-ok (func-that-throws-an-error))
 (test-error (func-that-throws-no-error))
 ;; and again some good tests
 (test-assert 1))

deftest test-2 () ;; even when an error is thrown outside a (test-... ) call we do not
 ;; crash but we cannot however simply continue.
 (test-ok (+ 1 1))
 (func-that-throws-an-error)
 (test-ok (+ 2 2)))

defun run-tests ()
 (test-1)
 (test-2))

(run-tests)

Calling run-tests will return the following output:

TEST-1: ...
x
 assertion failed for: (EQUAL 1 2)x
 call: (FUNC-THAT-THROWS-AN-ERROR) generated an error!x
 call: (FUNC-THAT-THROWS-NO-ERROR) DID NOT generate an error but you expected one!.
TEST-2: .x
 TEST-2 threw an unexpected error:
 foo bar
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