Simulation and Evaluation of Computer Networks

3. OMNeT++ – A Tool for Simulation Programming

- OMNeT++ - Some basic concepts
- Specifying module connections/topology
- Process-based modules
- Multiple random streams
- Working with OMNeT++ simulation programs
- Some odds and ends

Acknowledgement: These slides have been prepared by Prof. Dr. Günter Schäfer and Prof. Dr. Holger Karl (both TU Ilmenau)
Goals of this chapter

- The previous chapter has introduced basic notions of object-oriented programming for simulations: modules representing extended FSMs, communicating with events.
- This chapter introduces a tool that is based on these (and more) concepts, overcoming some of the deficiencies of the simple “tool” that we have developed.
- Particularly, means to:
  - Specify connections between modules
  - An additional programming style for modules
  - Structure larger simulation programs
  - Handle random numbers/variates for multiple purposes
  - Support debugging
- In general, this chapter shows a typical example of a simulation tool.
Overview

- **OMNeT++ - Some basic concepts**
- Specifying module connections/topology
- Process-based modules
- Multiple random streams
- Working with OMNeT++ simulation programs
- Some odds and ends
OMNeT++

- Objective Modular Network Testbed in C++ - OMNeT++ for short
  - [http://www.omnetpp.org](http://www.omnetpp.org)
- General-purpose tool for discrete event simulations
- Object-oriented design

- General structure:
  - *Modules* implement application-specific functionality
  - Modules can be connected by *connections*
  - Modules communicate by exchanging *messages* via connections
  - Modules are implemented as C++ objects, using support functions from a simulation library
  - Topology of module connections is specified using an OMNeT++-specific language called NED
OMNeT++ - Structure

- Overall structure: Modules with connections + simulation kernel
Modules

- All application-specific functionality is put into modules
- Modules exchange messages; arrival of a message at a module is an event
- As OMNeT++ is object-oriented, all modules are instances of certain classes, representing “module types”
- These classes must be derived from a specific class, `cSimpleModule`, an abstract class which provides basic functionality for a module
# Module example

```cpp
#include "omnetpp.h"

class MyModule : public cSimpleModule
{
    // calling constructors
    MyModule() : cSimpleModule() {}
    // user-specified functionality follows:
    ... ...
};

// announce this class as a module to OMNeT:
Define_Module(MyModule);
```
Module inheritance

User-defined module types can be used to derive new module types via standard inheritance techniques

```cpp
#include "MyModule.h"
class MyDerivedModule : public MyModule
{
    MyDerivedModule() : MyModule() {}
    // and again user-specific methods
    // follow
};
// and again make this class known as a module
Define_Module(MyDerivedModule);
```
Hierarchical structure of modules

- Modules of different types can be aggregated together to form a new, larger module type: a *compound* module.

- From outside a compound module, interior modules are not visible.

- Compound modules behave just like simple modules.

- Compound modules do not implement any functionality at all, only combine their constituent modules into a new module.

- Derived from `cCompoundModule`
  - Both `cSimpleModule` and `cCompoundModule` are derived from `cModule`.

- Enable hierarchical structuring of simulation programs.
OMNeT++ basic event handling

- As OMNeT++ is a tool for discrete event simulation, management of events is a primary task
  - Including event loop, managing the future event set, executing the next-event time advance mechanism, etc.
  - Taken care of by the simulation library itself

- Events are generated by modules sending messages to other modules or to themselves (often interpreted as timeouts)
  - Arrival of a message is interpreted as an event

- Module implementations
  - Need not concern themselves with the management of events
  - Only have to implement functionality to process the arrival of messages and
  - Have to send messages themselves (in general)
Module event handling

- Whenever a message arrives at a module, its `handleMessage()` method is invoked (completely analogous to our little simulation tool).
- `handleMessage()` is a virtual method provided by `cSimpleModule`, which a derived class has to override to implement some real functionality.
- `handleMessage()` processes the arrived message, potentially sending new message(s) itself, and returns to the caller (the simulation library).

- To be able to access the arrived message (along with its data), `handleMessage` is passed a pointer to the message, commonly represented by a `cMessage` object.
  - **Prototype is hence:** `void handleMessage(cMessage* msg);`
Processing messages in `handleMessage`

- Processing messages in general depends on the state of a particular module (e.g., is the server idle or busy?) and also manipulates the state.

- Such state variables are part of the information/knowledge of a module – hence, they are data members of the corresponding class:
  - Besides actual state information, all kinds of data pertaining to a module can be stored as data members: parameters for a module, its name or identification (e.g. server number), statistics about metrics, timer values, etc.
  - They are created with the corresponding module.

- In `handleMessage` these variables can be accessed and modified.
**Initializing module data members**

- Commonly, such data members are initialized in the constructor.
- However, a module constructor is called during the setup of an OMNeT simulation, when some information might not yet be easily available (e.g., total number of nodes in a simulation, etc.).
- `cSimpleModule` provides the virtual method `initialize()` as a convenient place for setting such data members to well-defined values.
- Additionally, `initialize()` can (and should) be used to generate some initial events.
  - If no module would generate any events at all, no event would ever happen, and the simulation would be rather static.
Shutting down modules

- As a counterpart to `initialize`, there needs to be some way to get data out of modules at the end of a simulation
  - E.g., statistics gathered about some interesting metrics
  - As not every module needs to know (or even should know) the stopping rule, it is not obvious to a module when to output this data

- `cSimpleModule` offers the `finish()` method as a convenient place

- At the end of a simulation run (determined by whatever mechanism), `finish()` of all modules is called by the simulation kernel
  - Allows modules to output statistics, perform clean up, ...
How to generate events/messages

- So far, only the consumption/reception of events/messages is described
- In `handleMessage()`, a module can decide to
  - Send a message to some other module: an entire family of `send()`-like methods is available
  - Schedule an event to be delivered to itself: `scheduleAt()`
    - E.g., setting a timeout after a packet has been sent
  - Cancel an event that has before been scheduled with `scheduleAt()`: method `cancelEvent()` will delete the specified event from the future event set
    - E.g., canceling a timeout when a packet has been received
- Question: Why is there no possibility to receive messages within `handleMessage()`, e.g., by calling a `recv()` function?
Example: Load generator

- Recall the load generator for an M/M/k queue: send a packet, wait some time, send a packet, ...
- Class declaration (e.g., loadgen.h)
  - Note that there are no data members (no state) needed for this example

```cpp
#include "omnetpp.h"
class Generator : public cSimpleModule {
    Generator() : cSimpleModule() {}
    virtual void initialize();
    virtual void handleMessage(cMessage *m);
};
Define_Module(Generator);
```
Example: Load generator

- Implementation (e.g., loadgen.cc)
- Initialization:

```c
void Generator::initialize() {
    scheduleAt(simTime(), new cMessage);
}
```

- **First argument of scheduleAt** is the time when the event should occur. Here: `simTime()`, which gives the current simulated time (akin to “now”) -> Event will occur immediately, after the `initialize` method has finished

- **Second argument** is a pointer to the message to be delivered. Here, just a pointer to a dynamically created message is inserted → message has no data, serves as a plain event
Example: Load generator

- Handling the event

```cpp
void Generator::handleMessage(cMessage* m) {
    cMessage* pkt = new cMessage;
    send(pkt, "out");
    scheduleAt(simTime() + exponential(1.0), m);
}
```

- First, another message is created (again without data) and sent “somewhere” (we will talk about the meaning of this shortly)

- Second, the message (event) that triggered this `handleMessage` invocation is scheduled again, to occur at some time now plus an exponentially distributed time (with mean 1.0) in the future
Adding data to messages

- The load generator’s message did not carry any data
- How to define messages that can carry data?
  - Rather: how to define „message types“?

- Message types are defined using a small definition language
  - Definitions are put in *.msg files
  - C++-code is generated automatically, child class of cMessage
  - Each message type ultimately corresponds to a separate C++ class

- Example: Create a message type „customer“
  - Contains a field „payload“ of type integer that can be set to a default value
  - File: customer.msg

```c++
message customer {
    int payload = 0;
}
```
Message inheritance

- Message types can be inherited
- Example: VIP customers with priority

```java
message VIPCustomer extends Customer { 
    int priority = 1;
}
```
Using message classes in code

- Example customer

```c
#include "customer_m.h"
...
Customer* newCustomer = new Customer("someCustomer");
newCustomer->setPayload(42);
....
int pl = newCustomer->getPayload();
```

- Getter and setter methods are automatically generated for each field
Detecting message type

- All generated message classes are descendants of cMessage
- In handleMessage, dynamic cast can be used to detect which type of message has actually arrived

```cpp
void dispatcher::handleMessage(cMessage* msg) {
    if(dynamic_cast<VIPCustomer*>(msg) != NULL) {
        VIPCustomer* vipMsg = static_cast<VIPCustomer*>(msg);
        // do something for important customers
    } else if(dynamic_cast<Customer*>(msg) != NULL) {
        Customer* nMsg = static_cast<Customer*>(msg);
        // normal customers ...
    }
    // ...
}
```
Remark: Complete FSM API in OMNeT++

- Besides the simple mechanism to code a finite state machine oneself based on the `handleMessage()` method, OMNeT++ provides an additional API to simplify the programming of finite state machines.
- Sets of states and actions for entering and leaving these states can be specified.
- API is realized as a set of macros – certainly possible to do it oneself, just a help to structure the code.
- Have a look at the manual.
Overview

- OMNeT++ - Some basic concepts
- **Specifying module connections/topology**
- Process-based modules
- Multiple random streams
- Working with OMNeT++ simulation programs
- Some odds and ends
Specifying module connections

- Basic idea: somehow specify connections between modules

- But: How can a module distinguish which connection leads to which module?
Gates as connection points for modules

- Additional construct: Module can have (an arbitrary number of) gates
  - Gates are identified by a number or by an index in a named array of gates
  - Gates are unidirectional: either an in-gate or an out-gate
- A connection simply connects an out-gate to an in-gate
Why use gates?

- Adding gates is just another level of complexity
- Why not have the module send directly to the peer module?
  - Reusability: a module should be useful in many contexts, without referring explicitly to other modules directly
  - Gates encapsulate the knowledge “where to” within the module
- Why not send directly to a connection?
  - Similar reason: connections can change, and do not have a real identity of their own (only specified by the two modules they are connecting)
- Gates turn modules into black boxes with well defined interfaces/“service access points with protocols”
Communicating using gates

- Modules can send messages directly to a specific out gate:
  ```c
  send (pkt, "myoutgate1");
  ```

- Modules can find out on which in-gate a message has arrived
  - `cMessage` objects represent not only the message as such, but also meta information about the particular message
  - E.g., `cMessage` provides a method
    ```c
    cGate* getArrivalGate();
    ```
    which returns a pointer to the gate at which the message arrived
  - `cGate` is a class representing gates in OMNeT++
    - In `send`, the string name of a gate will implicitly be converted to the corresponding pointer
How to specify gates and their connections?

- So far, we have not seen any constructions in the class definition that would specify a gate or a connection between gates.

- In fact, OMNet++ uses a separate language to specify topology of an entire network of modules: the NEtwork Description language (NED).

- For each simulation program, a NED file is required.

- It describes:
  - Channels (to be used as connections between modules)
  - Simple modules (declarations, to be implemented as a C++ class)
  - Compound modules (discussed later)
  - Connections between modules within compound modules
NED channel definition

- Channels represent types of connections
- Parameterized by delay, error rate (uniformly distributed), and data rate
- Example:

  ```
  channel DialUpConnection {
    delay normal(0.004, 0.0018);
    error 0.00001;
    datarate 14400;
  }
  ```

- `DialUpConnection` can later be used as a connection type
- Note: delay is parameterized with a normal distribution, not a specific value -> for every connection of this type, a new delay is randomly chosen from a normal distribution with these parameters
- General concept of NED: where a value is legal, a random distribution is also acceptable
NED simple module definitions – Parameters

- Simple modules are defined in NED file by their
  - Parameters
  - Gates
- Parameters of simple modules
  - Values that can be set from outside the simulation program, e.g., in configuration files
  - Parameters can be easily accessed from the C++ code using `cModule`'s method `par("parametername")`
- Example:
  ```c++
  simple LoadGenerator {
  parameters:
  double interarrival_time;
  gates: …
  }
  ```
- Using the parameter in
  ```c++
  LoadGenerator::someMethod():
  float intarrtime = (float)par("interarrival_time");
  ```
NED simple module definitions – Gates

- In NED, the gates of simple modules are defined as well, as either in or out gates
- Example

```plaintext
simple DataLinkProtocol {
  parameters: ...
  gates:
    input from_upper_layer;
    input from_physical_layer;
    output to_upper_layer;
    output to_physical_layer;
}
```
NED simple module definitions – Gates

- Gates can also be defined as arrays:

```plaintext
simple RoutingModule {
    parameters: ...
    gates:
        input in[];
        output out[];
}
```

- Size of the vectors need not be defined immediately but can be supplied later
  - Size can be different for multiple instances of the same type
  - Example: different RoutingModules have different numbers of in and out links
NED compound modules

- Compound modules consist of one or more submodules
- To the outside: behave like any other modules -> must offer gates
- To the inside: composing modules must be able to communicate somehow -> their gates must be connected
- Relating outside and inside: gates of the compound module are connected to (some) gates of (some) of the composing modules
NED compound modules – Syntax

- Parameters of compound modules are similar to simple modules
  - Can be used to set parameters of contained modules
  - Can be used to compute connections (see below)
- Gates of compound modules are identical to simple module gates

```
module SomeCompoundModule
{
    parameters: ...
    gates: ...
    submodules: ...
    connections:
}
```
NED compound modules – Submodules

- Submodules section of a compound modules defines which modules (and their module types) constitute the compound module
- For parameterized module types, the parameters have to be provided
  - General parameters as well as sizes of gate vectors (if any)
- Submodules can be written as vectors of modules

```markdown
module BigCompound{
    parameters:
        num_of_submods: const;

    submodules:
        node[num_o_submods/2] : Node;
}
```

- Module type of submodules need not be specified explicitly, can be left as a parameter
NED compound modules – Connections

- Specify connections between gates
  - Of the compound modules to gates of its constituent modules
  - Of the constituent modules themselves
- Connections can not “cross border lines” of modules
- Connections can be endowed with parameters (delay, error, bandwidth) or channel types
NED compound modules – Connections

- Simple programming constructs (for loops, if conditions) allow to construct complicated topologies of connections
  - Example: Normally, all gates must be connected after program has initialized. Sometimes, however, only partially connectivity is desired -> “nocheck” primitive

```plaintext
module Stochastic {
    connections nocheck:
    for i=0 .. 9 {
        Sender.outgate[i] -> Receiver[i].ingate if uniform(0,1) < 0.3;
    }
    ...
}
```
Relating NED file to C++ classes

- Simple modules of name X are implemented by a C++ class of name X
  - Recall the macro `Define_Module(X)` after the definition of a C++ class
  - This macro couples the class to the NED module type
  - Usually put in file X.h and X.cc, but that is not required

- Compound modules do not have a corresponding C++ class at all
Relating NED file to C++ classes

- A module type can be implemented by different classes which share the same interface
  - Define_Module_Like (X, Y): class X implements NED module Y’s interface
  - Example: Different types of MAC layers all sharing the same interface
    - Define_Module_Like(Ethernet_MAC, General_MAC);
    - Define_Module_Like(TokenRing_MAC, General_MAC);
    - Define_Module_Like(FDDI_MAC, General_MAC);

- Such a module type can not directly be used within a compound module, however, it can be used as a placeholder to be instantiated with the actual type of the submodule from some initialization mechanism
  - Example:

```
submodules:
    mac : mac_type like General_MAC
```

- mac_type can later be assigned any of Ethernet_MAC, TokenRing_MAC, FDDI_MAC
- In configuration file, write something like: `mac_type = TokenRing_MAC`
Overview

- OMNeT++ - Some basic concepts
- Specifying module connections/topology
- **Process-based modules**
- Multiple random streams
- Working with OMNeT++ simulation programs
- Some odds and ends
Reconsider the load generator module

The load generator module can be implemented as a finite state machine:
- Upon receipt of a message (where the content of the message is irrelevant), generate a “load” message to be delivered immediately and a self message to be delivered some time later
- The self message only serves to trigger a new cycle

What the load generator actually does:
- Repeatedly wait some random time, then send a message
- Modeling such a process as a finite state machine is somewhat awkward

Would it not be nice to be able to explicitly model such processes that have a distinctive flow of control?
Processes in a simulation

- Such a process should be able to
  - Receive messages
  - Manipulate inner state
  - Send messages
  - And wait for some arbitrary amount of time
    - Example: To model the time necessary to analyze a message, a process-based simulation would just wait

- During such waiting, the process would not be able to react to any messages
  - In contrast to a finite-state simulation, which is “always” able to receive messages, as the processing of messages and performing state transmission takes zero simulated time
Using processes in OMNeT++

- OMNet++ supports both finite state/event-based simulation as well as process-based simulation
- A module can implement a single process
- Instead of implementing `handleMessage`, a process-based module class implements the `activity` method
  - Strictly exclusive: a module is either event- or process-based
  - Different modules can use different paradigms (one of OMNeT’s main advantages!)
Process-based modules

- **Within activity**, a module can:
  - receive messages (different functions available)
  - send messages (different functions available)
  - wait – to suspend its own execution for a specified amount of simulated time
  - scheduleAt – module sends a message to itself
  - cancelEvent – delete an event scheduled with scheduleAt
  - end – terminate its own execution

- **Not available in handleMessage**
  - receive – useless, as handleMessage already is the reaction to the reception of a message
  - wait – processing event takes no time for a finite state machine
  - end – due to implementation issues
Process-based modules

- Typical structure of activity: Infinite loop, containing at least a single wait or receive call
  - What if both are absent?

- Local state of a module can be put into data members of the class as in the event-based case, here, an alternative exists
  - activity is run as a coroutine, having its own stack, for each module instance
  - Think of activity as a thread running in parallel with all other parts of the simulation
  - Hence, activity has local variables which maintain value even across receive and wait calls
  - Local module state can be stored in local variables of activity
Process-based modules

- Running activity as a coroutine requires to set aside memory for the stack
  - Stack is specified in the constructor for a module, called by the `Module_Class_Members` macro:

```cpp
class ProcessModule : public cSimpleModule {
    public:
    ProcessModule() : cSimpleModule(8192) {}
}
```

- Specifying a stack in this macro distinguishes between an event- and process based module implementation

- `initialize()` is not necessary, can be done at the start of activity
- `finish()` is required to output statistics at end of simulation
Process-based modules – typical setup

class MyProcessBasedModule : public cSimpleModule {
    // variables for statistics gathering
    activity();
    finish();
}

MyProcessBasedModule::activity () {
    declare local variable to hold state, initialize them
    initialize statistics gathering variables
    while (true)
    { ... (usually send, receive, wait, ...) }
}

MyProcessBasedModule::finish() {
    record statistics data into a file
}
Comparing event and process style

- Advantages of process-based style
  - `initialize()` is not required
  - State can be stored in local variables of `activity()`
  - Process-based style can be natural programming model

- Advantages of event-based style
  - Lower memory overhead (no separate stack required)
  - Faster: switching to coroutines takes longer than just calling a method (handleMessage)
Comparing event and process style

- Event-based is usually better if
  - Module has little or no state (e.g., data sinks)
  - Module has large state space, where many arbitrary transitions between any two states exist, i.e., there is no clear succession from one state to a successor state – typical for communication protocols

- Rule of thumb:
  - If activity looks like a loop which only switches on the message type, convert it to `handleMessage`
Overview

- OMNeT++ - Some basic concepts
- Specifying module connections/topology
- Process-based modules
- *Multiple random streams*
- Working with OMNeT++ simulation programs
- Some odds and ends
Using multiple random streams

- As mentioned already, different random number streams must be used for
  - Different simulation runs
  - Different sources of randomness within a simulation to avoid unwanted correlation
- OMNeT++ provides 32 independent random number generators (by default, can be extended)
- Most simply, one generator can be accessed with
  - intrand() – produces an integer between 1..INTRAND_MAX-1
  - randseed(x) – set seed of first generator to x
Using multiple random streams

- To access another one of the 32 available generators, use:
  - `genk_intrand(k)` – random number from generator k
  - `genk_randseed(k, x)` – set seed of generator k to x

- To obtain double randoms between 0 and 1:
  - `dblrand()` and `genk_dblrand()`

- To obtain numbers from certain distributions
  - `double genk_uniform(...)`
  - `double genk_intuniform(...)`
  - `double genk_exponential(...)`
  - `double genk_normal(...)`
  - `double genk_truncnormal(...)`

- Additional distributions can be implemented, and, when registered using `Register_Function`, even used in NED expressions
Choosing seeds

- Choosing good seeds for RNGs is a difficult problem
- Latest OMNeT++ versions have automatic seed selection (based on runs)
- `seedtool` can be used to generate sufficient number of seeds (manual method)
- Example: four runs of a simulation that need two different RNGs, each needing at most 10,000,000 random numbers
  - `seedtool g 1 10000000 8` will generate the required eight seed values for streams that are 10,000,000 values apart
  - Details see manual
- How to easily use these seed values in simulations runs will be described later
Overview

- OMNeT++ - Some basic concepts
- Specifying module connections/topology
- Process-based modules
- Multiple random streams
- Working with OMNeT++ simulation programs
  - Building and running
  - Debugging support
  - Collecting and displaying measurements
- Some odds and ends
Parts of OMNeT++ programs

- An Omnet program consists of a collection of modules
  - Set of `bla.cc` and `bla.h` file for each class `bla`
- A `*.ned` file is required to specify network connectivity
  - Strictly speaking, not really required: a program can generate the entire network (modules+connections) dynamically – check the manual on how to do this
- Additionally, the file `omnetpp.ini` is required, containing general settings about the execution of the simulation
  - More details later

- How to turn this into an executable?
Building an OMNeT++ program

- Usually, a make file is required, listing dependencies between separate files and instructions about libraries to include in a program.

- Omnet provides a little tool `opp_makemake` to generate a makefile.
  - Usage: call `opp_makemake`
  - Call `make depend` to generate dependencies on `.h`-files
  - `make` will build the program

- `opp_makemake` collects all `*.cc` files in the current directory and includes them in the program-to-be-built.
  - Required libraries and theirs paths are also bound to the program
  - Possible to select between statically and dynamically linked programs
Running an OMNeT++ program

- OMNeT programs can be run under two user interfaces: command-line oriented or graphical user interface
  - Selected as a parameter to `opp_makemake`

- Graphical user interface
  - Represents modules and connections, messages traveling along connections
  - Single-step from event to event or run the program with different animation speeds
  - Inspectors for most objects (e.g., double-click on modules)

- Command-line interface
  - Rather uncomfortable, use it to run a program at maximum speed after it has been debugged with the graphical interface
omnetpp.ini

Initialization file, contains several sections

- General settings: warning levels, names for output files, seed selection, limits on the simulation and simulated time, maximum memory usage, using parallel execution, etc.

- Environment-specific settings
  - Command-line: which runs to execute (see below), level of verbosity
  - Graphical environment: speed and level of detail of animation, etc.

- Parameters: any parameters that were unspecified in the ned-file can be set here
  - Any parameter left unset will be requested from the user at program startup

- Runs: the same program can be executed multiple times with different parameter settings – a run

- Possible to specify when to start/stop taking measurements
Debugging aids

- **Printf-style debugging** is supported with the `ev` object, using normal `<<` I/O operator
  - Can be collected in different ways for compound modules
  - Do never use `printf`, `cout` etc. as this will conflict with the graphical environment (will appear in `xterm` from which program is started)
  - `setPhase()` to set title of windows

- **Watchers**
  - A watch can be declared for primitive variables
  - Watched variables can be inspected/changed in the GUI and output into a snapshot
  - Syntax:
    ```
    int i;
    WATCH(i);
    ```
Debugging aids

- **Snapshots**
  - Dump status of the entire (or selected parts of) simulation into a text file (default: `omnetpp.sna`) via `snapshot()`
  - Modules, queues, message queues, watched variables, etc. can be included

- **Breakpoints**
  - In `activity()`, breakpoints can be set by calling function `breakpoint`, execution will be suspended
  - Only available if user interface supports debugging
  - Setting Breakpoints via the Debugger in the OMNET IDE or via an external debugger like `gdb`

- **Warnings can be disabled**

- **Stack usage can be checked**
  - Can be substantial with `coroutines/activity()` as they need a lot of space on the stack
Collecting measurements

- OMNeT provides several statistic classes to collect results
  - `cStdDev` collects samples, computes mean, standard deviation, number of samples, min, max
  - `cWeightedStdDev`: similar, but weighted, e.g. to compute time-averaged statistics
  - `cLongHistogram/cDoubleHistogram`: additionally store an approximated density
- These classes also provide hooks to interact with classes for transient detection and accuracy estimation of results
- Details later
- Some other classes – read the manual!
Extracting measurements

- Two main supporting mechanisms are offered:
  - Outputting scalar measurements at the end of a simulation run
  - Outputting vector-like measurements during a simulation

- Scalar measurements
  - `recordScalar("bla", value)` writes an entry into `omnetpp.sca`
  - `recordStatistic` to write a statistic object to that file (e.g. `cHistogram`, `cWeightedStdDev`)
  - Usually done in `finish()` methods of a simple module

- Vector measurements
  - Class `cOutVector` provides functionality
  - Create an object e.g. `value_vector` of this class, along with a name
  - Call `value_vector.record(value)` to write an entry into `omnetpp.vec`
    - Generates a single line in this file
    - Note: vector file is deleted at the beginning of each run
Visualizing measurements

- General remark: Make SURE you can generate visualizations automatically
  - You are going to run many many different simulation experiments with identical result formats
  - You do not want to point-and-click every time the same sequence of commands
  - Hence, visualizations MUST be batch-able!

- Main keywords: perl/ruby/python, R and gnuplot
  - Or equivalent tools, but nothing GUI-point-and-click-ish!

- Nice intermediate tools integrated into OMNeT IDE for basic data visualization
  - Knows how to “read in” OMNeT‘s vector output

- And even better: add some little script code that generates LaTeX-wrappers for the figures as well
Some odds and ends

- Above all: READ THE MANUAL!
- OMNeT has an extensive simulation library
  - Contains container classes like queues (cQueue) and other useful stuff
- The way messages have been described here is rather inefficient
  - Handling cPar objects to manipulate data of a message is processing intensive
  - Subclassing of cMessage can provide immense speedup
- Look at coding conventions and tips for speeding up the simulation in the manual
- OMNeT++ can make use of PVM-based parallel execution
Conclusions

- OMNeT++ is an extensive discrete event simulation system
  - Cleanly structured object-oriented design
  - Provides access to both event- and process-based programming style
  - A lot of support functionality

- Experience is needed to make best use of its potential
  - But has a comparatively smooth learning curve (other tools are much worse)