ns-3 Training

Session 1: Monday May 11

ns-3 Annual meeting
May 2015

Introduction and logistics

- CTTC facilities
- Meals and coffee
- Wi-Fi
- Wiki page:
  - **https://www.nsnam.org/wiki/AnnualTraining2015**
- Meet your instructors

Monday agenda

- Monday
  - ns-3 survey and overview tutorial, starting from first principles and walking through the running of simulations, configuration management, architecture of the software core, network emulation, and development practices using ns-3.
  - Methodology and workflow for developing new models in ns-3, using a case study.
  - Several tools used to extract and visualize data from ns-3 simulations, including the flow monitor,network animator NetAnim, Python-based visualizer, and the ns-3 tracing system.

Tuesday agenda

- Tuesday
  - (09:00-10:30) Large-scale, distributed simulations with ns-3 (instructor: Peter Barnes)
  - (11:00-12:30)An introduction to the Direct Code Execution (DCE) environment, enabling users to use real application and Linux networking code in ns-3 (instructor: Hajime Tazaki)
  - Lunch break
  - (14:00-16:00) A survey of the LTE models, including model architecture, propagation models, LTE Radio Protocol Stack and EPC model. (instructor: Nicola Baldo)
  - 16:30-18:00) A tutorial on vehicular communication simulations, including mobility, WiFi and WAVE models, and propagation. (instructor: Konstantinos Katsaros)

Later in the week

- WNS3 Wednesday and Thursday morning
- ns-3 Consortium Annual Meeting (16h00 Thursday)
- Developer meetings Friday

ns-3 training goals

- Learn about the project scope, and where to get additional help
- Understand the architecture and design goals of the software
- Introduce how to write new code for the simulator
- Learn about selected topics in more detail
- Answer your questions

Motivations for ns-3 project

Develop an extensible simulation environment for networking research

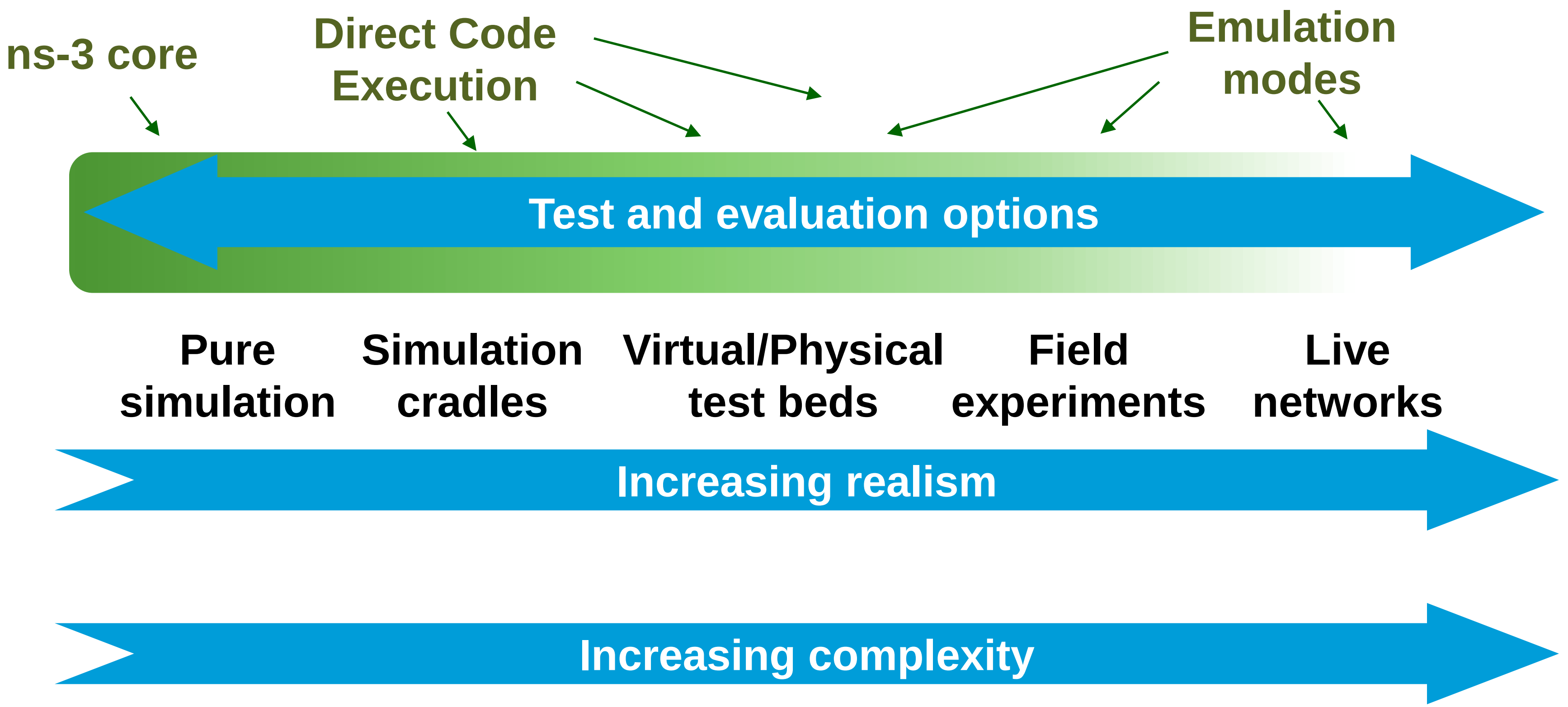
1) a tool **aligned with the experimentation needs** of modern networking research

2) a tool that **elevates the technical rigor** of network simulation practice

3) an **open-source project** that encourages community contribution, peer review, and long-term maintenance and validation of the software

Network performance evaluation options

- ns-3 enables researchers to more easily move between simulations, test beds, and experiments



ns history

1990

2000

2010

1988: REAL (Keshav)

1990s: ns-1

1996: ns-2

1997-2000: DARPA VINT

2001-04: DARPA SAMAN, NSF CONSER

2006: NSF CISE CRI Awards

Inputs: yans, GTNetS, ns-2 ⇨ ns-3 core development (2006-08)

June 2008: ns-3.1

regular releases

May 2015: ns-3.23

Relationship to ns-2

ns-3 is a new simulator, without backward compatibility

Similarities to ns-2:

- C++ software core
- GNU GPLv2 licensing
- ported ns-2 models: random variables, error models, OLSR, Calendar Queue scheduler

Differences:

- Python scripting (or C++ programs) replaces OTcl
- most of the core rewritten
- new animators, configuration tools, etc. are in work
- ns-2 is no longer actively maintained/supported

How the project operates

- Project provides three annual software releases
- Users interact on mailing lists and using Bugzilla bug tracker
- Code may be proposed for merge
  - Code reviews occur on a Google site
- Maintainers (one for each module) fix or delegate bugs, participate in reviews
- Project has been conducting annual workshop and developer meeting around SIMUTools through 2013
  - Some additional meetings on ad hoc basis
- Google Summer of Code (March-August) six of the past seven summers

Sustainment

- The NS-3 Consortium is a collection of organizations cooperating to support and develop the ns-3 software.
- It operates in support of the open source project
  - by providing a point of contact between industrial members and ns-3 developers,
  - by sponsoring events in support of ns-3 such as users' days and workshops,
  - by guaranteeing maintenance support for ns-3's core, and
  - by supporting administrative activities necessary to conduct a large open source project.

Publications using ns-3

A common question is "How many ns-3 papers are there?

- Small survey of 139 paper results from 2013-14 search of IEEE library (top relevant results)
- Some papers matched multiple categories
- Hot topics:
  - LTE/cellular networks (15)
  - Wireless routing protocols (14)
  - Sensor networks (13)
  - Wireless MAC and PHY protocols (11)

Paper counts by topic

Topic	Count		Topic	Count
LTE/Cellular	15		Network coding	4
Wireless routing protocols	14		Datacenter networks	4
Wireless sensor networks	13		Distributed systems	4
Wireless MAC/PHY	11		Optical links	3
Wireless QoS	9		Misc. physical links	3
Vehicular networks	9		Multicast	3
TCP/congestion control	9		Misc. security	2
Wireless security	9		Wired routers	2
About ns-3 itself	8		Wireless QoS	2
Wifi/mesh networks	7		WiMAX	1
Voice/video apps	6		Mobility	1
Energy/resource consumption	6		Misc. routing	1
DTN and space networks	5		Miscellaneous	1
Misc. wireless	5			

ns-3
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Acknowledgment of support

National Science Foundation
WHERE DISCOVERIES BEGIN

Naval Research Laboratory, Washington, DC

Inria informatics mathematics

PLANETE

University of Washington 1861

Georgia Tech

Google Summer of Code 2012

INESC PORTO
LABORATÓRIO ASSOCIADO

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

ISI
Information Sciences Institute

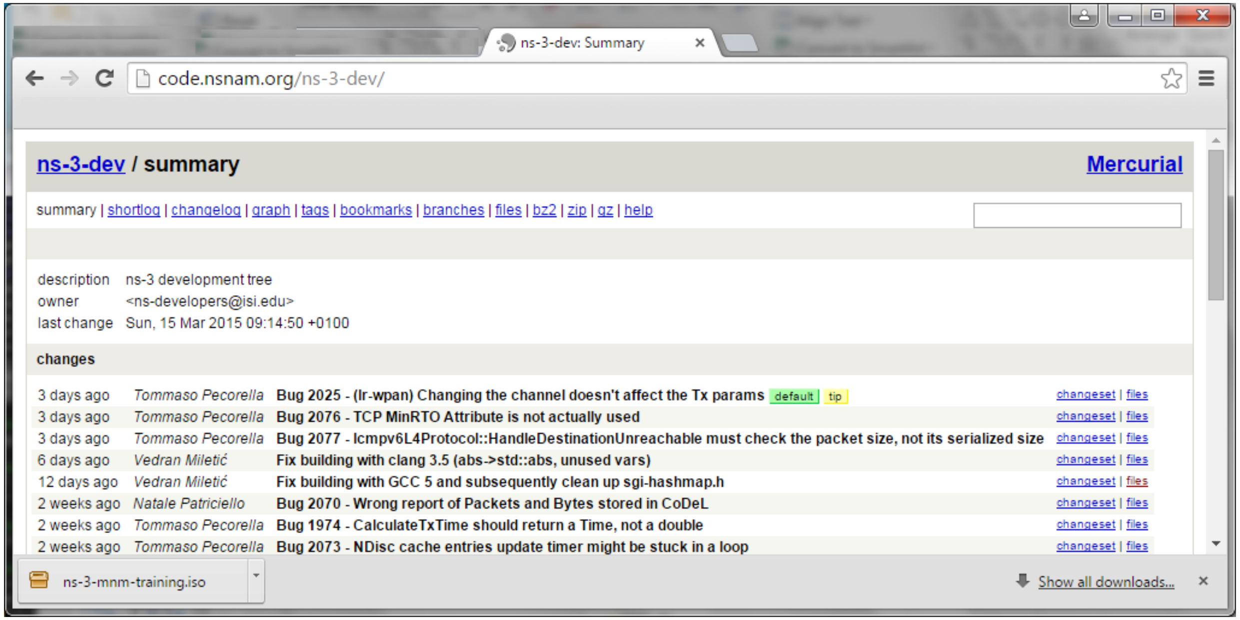
- Software overview

Options for working along

1) Download the required packages onto your (Linux, OS X, or BSD) system

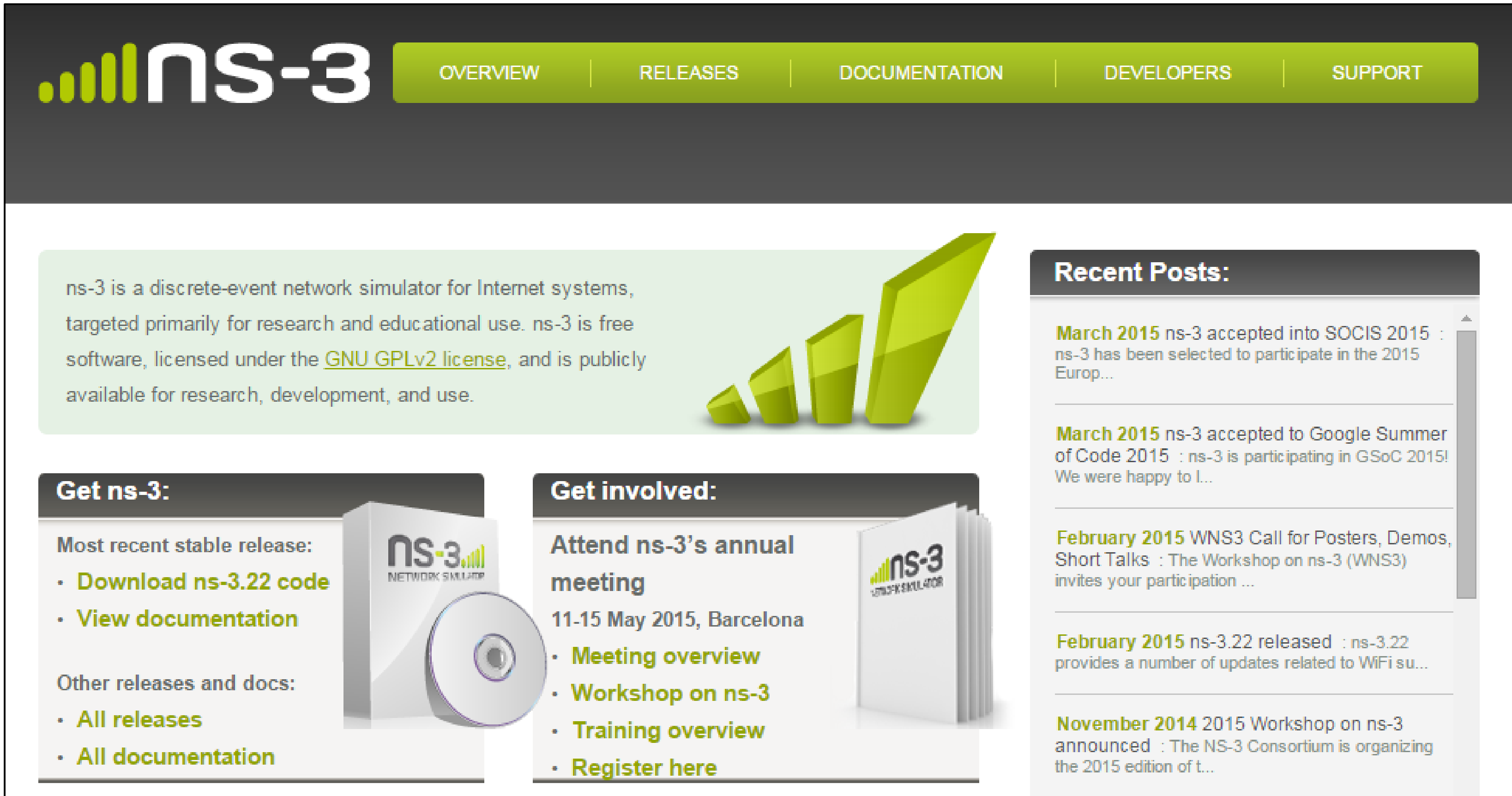
2) Download or copy the ISO image (Live DVD)

3) Browse the code online: https://code.nsnam.org



ns-3 main website

- Project home: https://www.nsnam.org



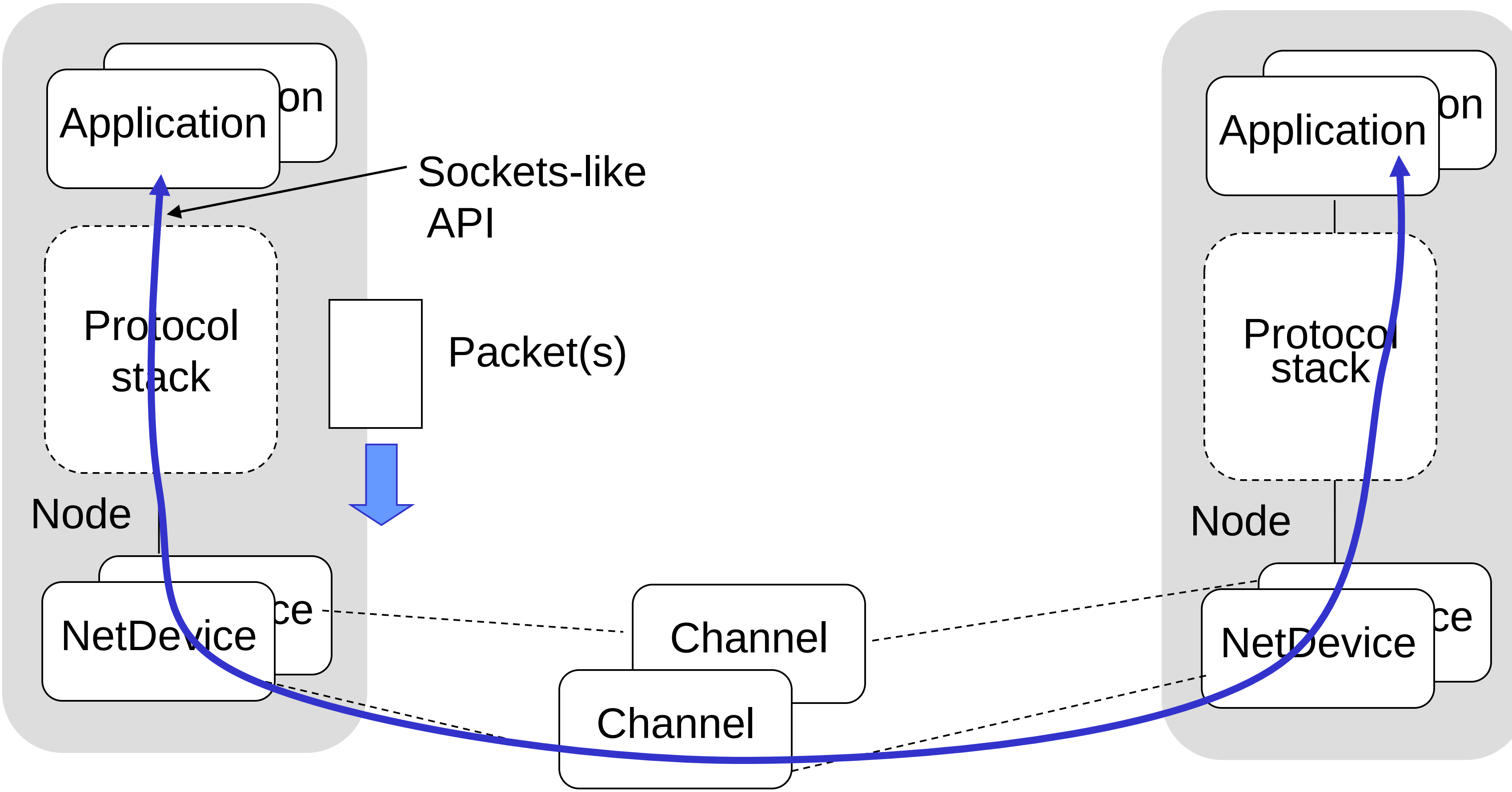
Software overview

- ns-3 is written in C++, with bindings available for Python
  - simulation programs are C++ executables or Python programs
  - ~350,000 lines of C++ (estimate based on cloc source code analysis)
- ns-3 is a GNU GPLv2-licensed project
- ns-3 is mainly supported for Linux, OS X, and FreeBSD
  - Windows Visual Studio port available
- ns-3 is not backwards-compatible with ns-2

Discrete-event simulation basics

- Simulation time moves in discrete jumps from event to event
- C++ functions schedule events to occur at specific simulation times
- A simulation scheduler orders the event execution
- Simulation::Run() executes a single-threaded event list
- Simulation stops at specific time or when events end

The basic ns-3 architecture



Software orientation

Key differences from other network simulators:

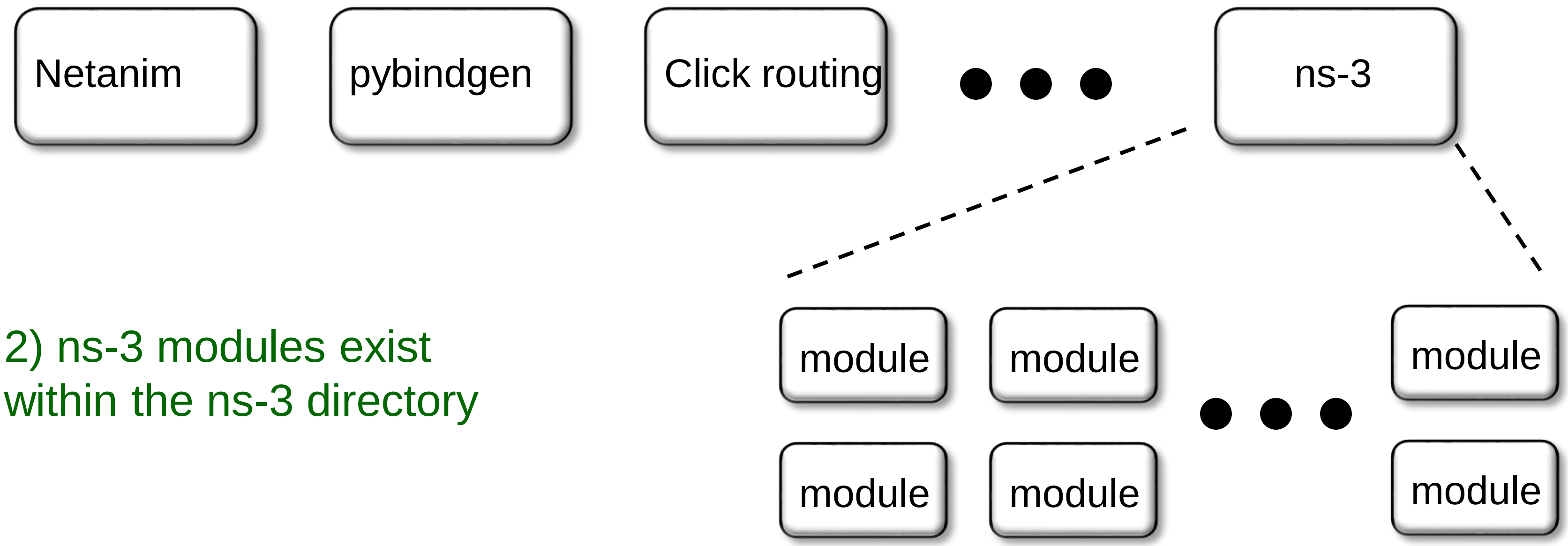
1) Command-line, Unix orientation
   - vs. Integrated Development Environment (IDE)

2) Simulations and models written directly in C++ and Python
   - vs. a domain-specific simulation language

Software organization

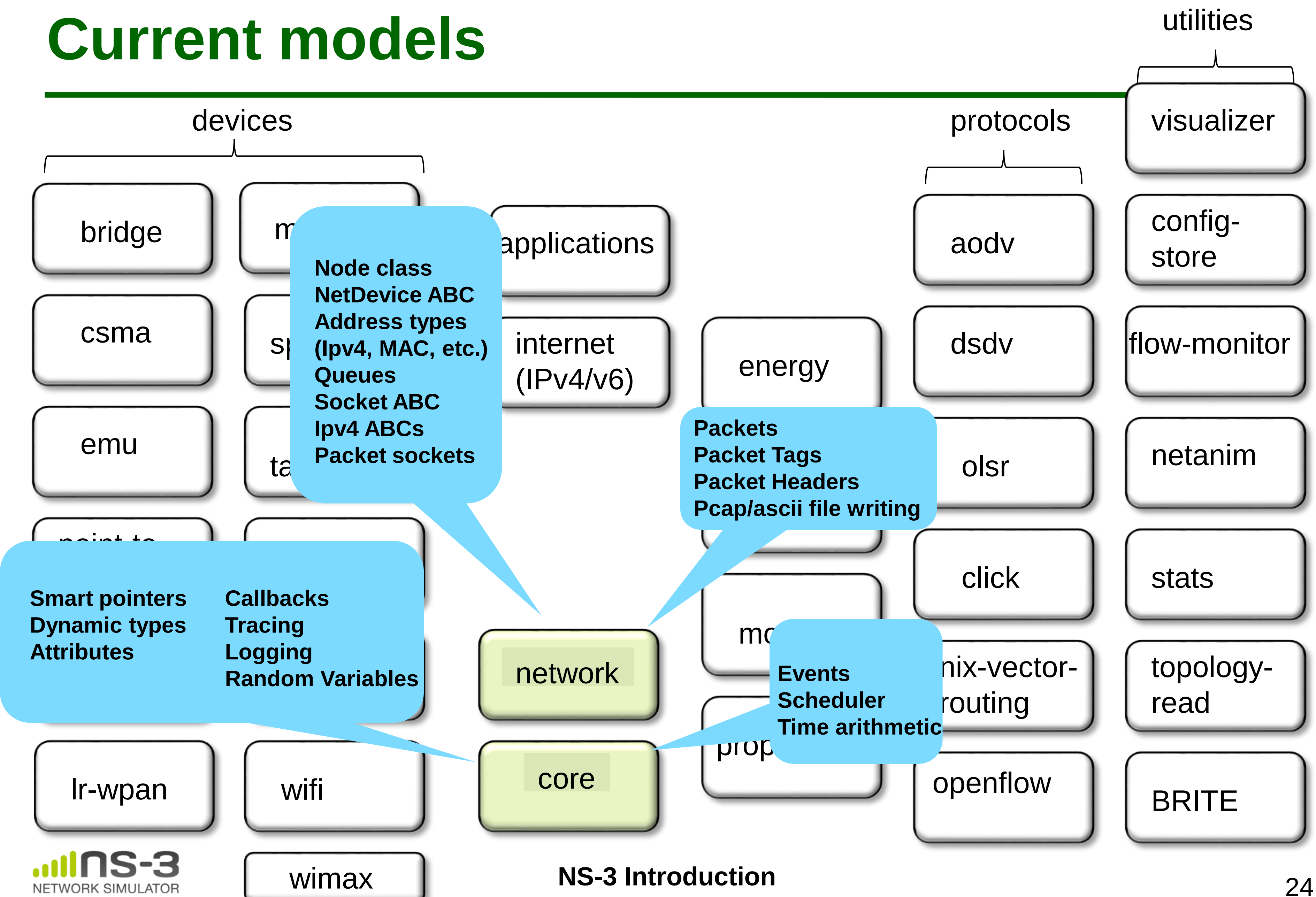
- Two levels of ns-3 software and libraries

1) Several supporting libraries, not system-installed, can be in parallel to ns-3



2) ns-3 modules exist within the ns-3 directory

Current models



Module organization

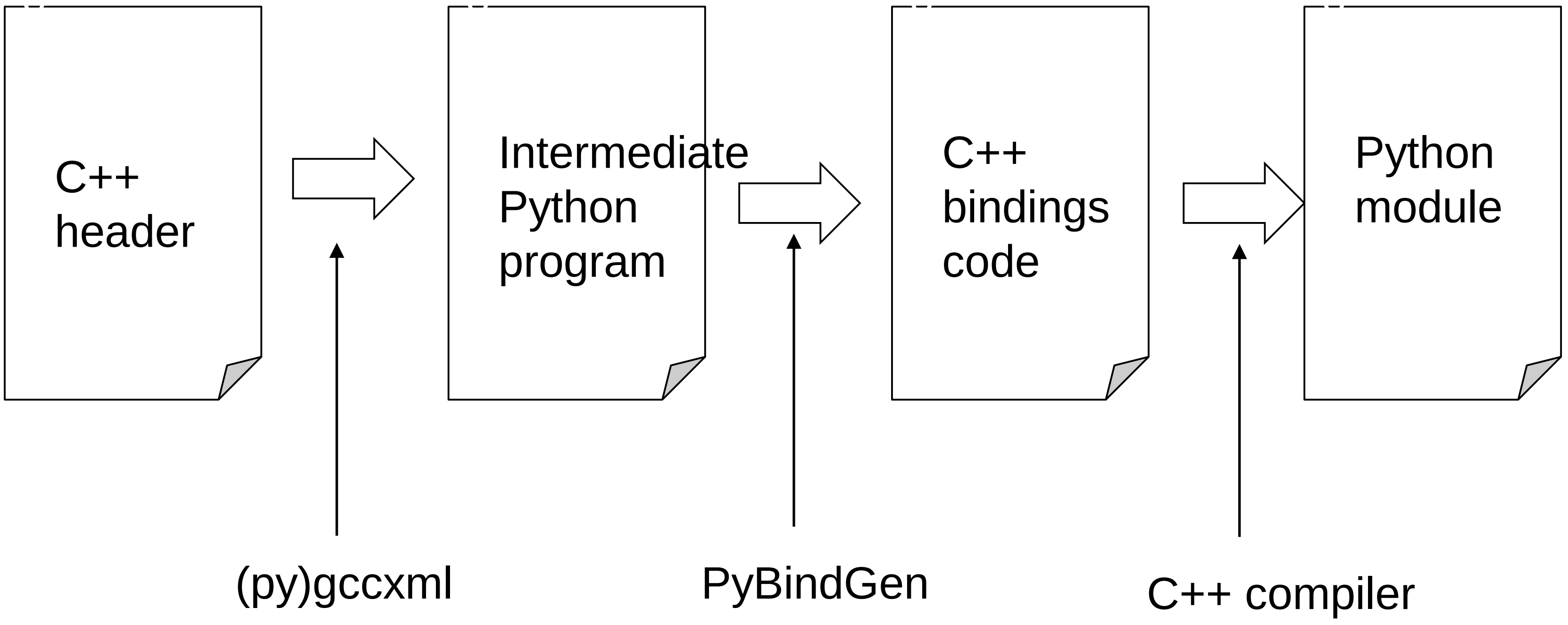
- models/
- examples/
- tests/
- bindings/
- doc/
- wscript

ns-3 programs

- ns-3 programs are C++ executables that link the needed shared libraries
  - or Python programs that import the needed modules
- The ns-3 build tool, called 'waf', can be used to run programs
- waf will place headers, object files, libraries, and executables in a 'build' directory

Python bindings

- ns-3 uses a program called PyBindGen to generate Python bindings for all libraries



Integrating other tools and libraries

Other libraries

- more sophisticated scenarios and models typically leverage other libraries
- ns-3 main distribution uses optional libraries (libxml2, gsl, mysql) but care is taken to avoid strict build dependencies
- the 'bake' tool (described later) helps to manage library dependencies
- users are free to write their own Makefiles or wscripts to do something special

Gnuplot

- `src/tools/gnuplot.{cc,h}`
- C++ wrapper around gnuplot
- classes:
  - `Gnuplot`
  - `GnuplotDataset`
    - `Gnuplot2dDataset, Gnuplot2dFunction`
    - `Gnuplot3dDataset, Gnuplot3dFunction`

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Enabling gnuplot for your code

- `examples/wireless/wifi-clear-channel-cmu.cc`

```
CommandLine cmd;
cmd.Parse (argc, argv);

Gnuplot gnuplot = Gnuplot ("clear-channel.eps");

for (uint32_t i = 0; i < modes.size (); i++)
  {
    std::cout << modes[i] << std::endl;
    Gnuplot2dDataset dataset (modes[i]);
```

produce a plot file that will generate an EPS figure

one dataset per mode

```
    uint32_t pktsRecvd = experiment.Run (wifi, wifiPhy, wifiMac, wifiChannel);
    dataset.Add (rss, pktsRecvd);
  }

gnuplot.AddDataset (dataset);
```

Add data to dataset

Add dataset to plot

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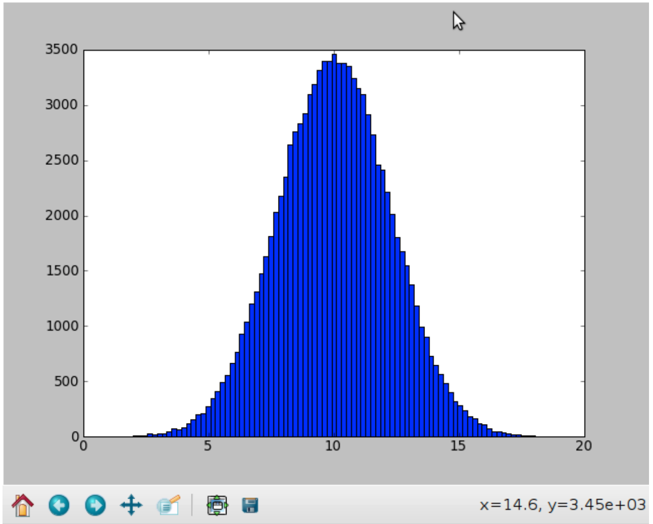
Matplotlib

- src/core/examples/sample-rng-plot.py




```
# Demonstrate use of ns-3 as a random number generator integrated
# plotting tools; adapted from Gustavo Carneiro's ns-3 tutorial

import numpy as np
import matplotlib.pyplot as plt
import ns.core

# mu, var = 100, 225
rng = ns.core.NormalVariable(100.0, 225.0)
x = [rng.GetValue() for t in range(10000)]

# the histogram of the data
n, bins, patches = plt.hist(x, 50, normed=1, facecolor='g', alpha=0.75)

plt.title('ns-3 histogram')
plt.text(60, .025, r'$\mu=100,\ \sigma=15$')
plt.axis([40, 160, 0, 0.03])
plt.grid(True)
plt.show()
```

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Click Modular Router

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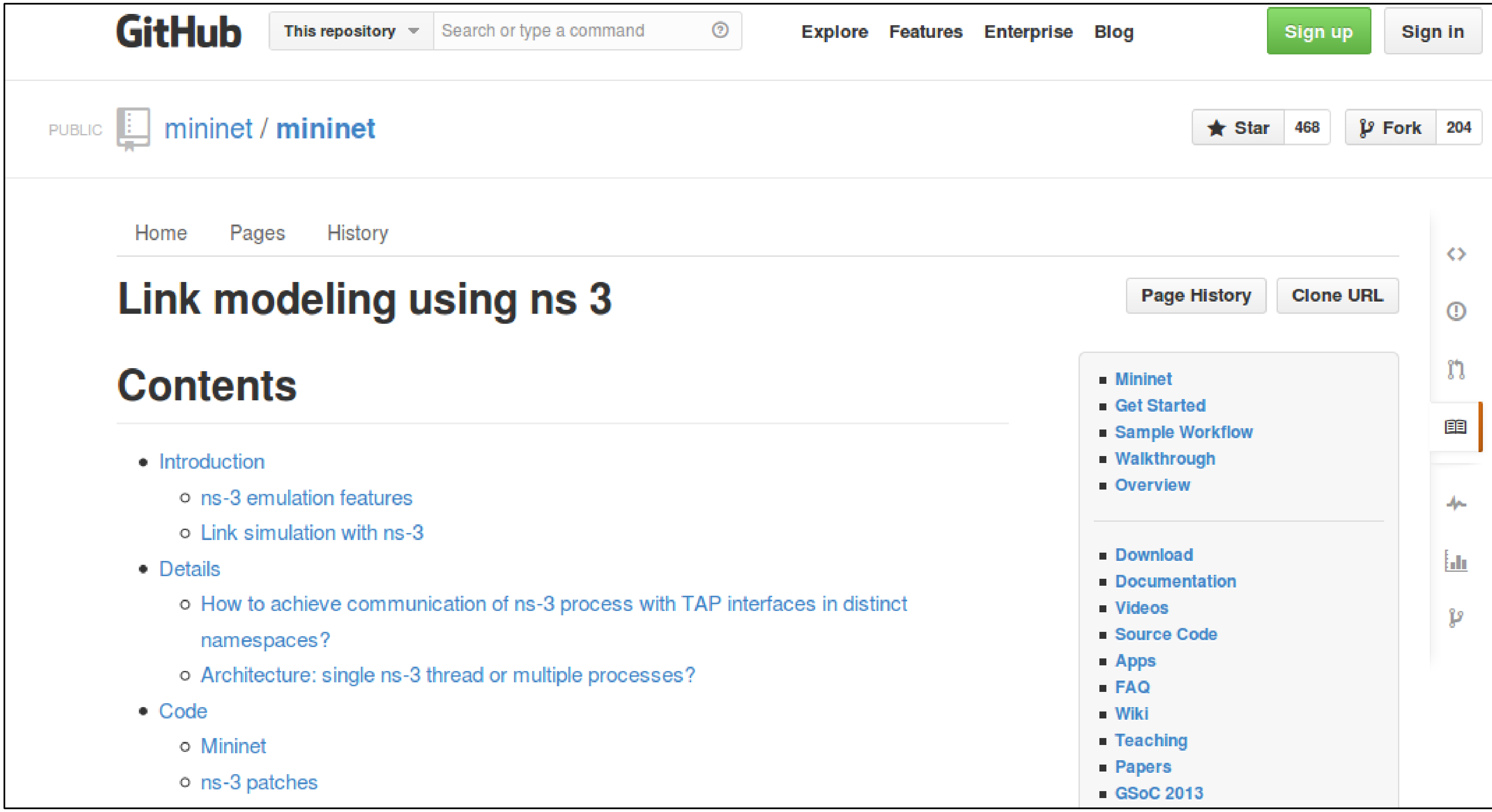
The Click Modular Router Project

NEWS (September 24, 2011): **Click 2.0.1 released!**

SyClick: Symposium on Click Modular Router was **November 23-24, 2009, Ghent, Belgium!** An excellent time was had. Video of the presentations is now available.

This is the DokuWiki for the Click modular router. Click was originally developed at MIT with subsequent development at Mazu Networks, ICIR, UCLA, and Meraki.

mininet emulator



Co-simulation frameworks have emerged

- PNNL's FNCS framework integrates ns-3 with transmission and distribution simulators

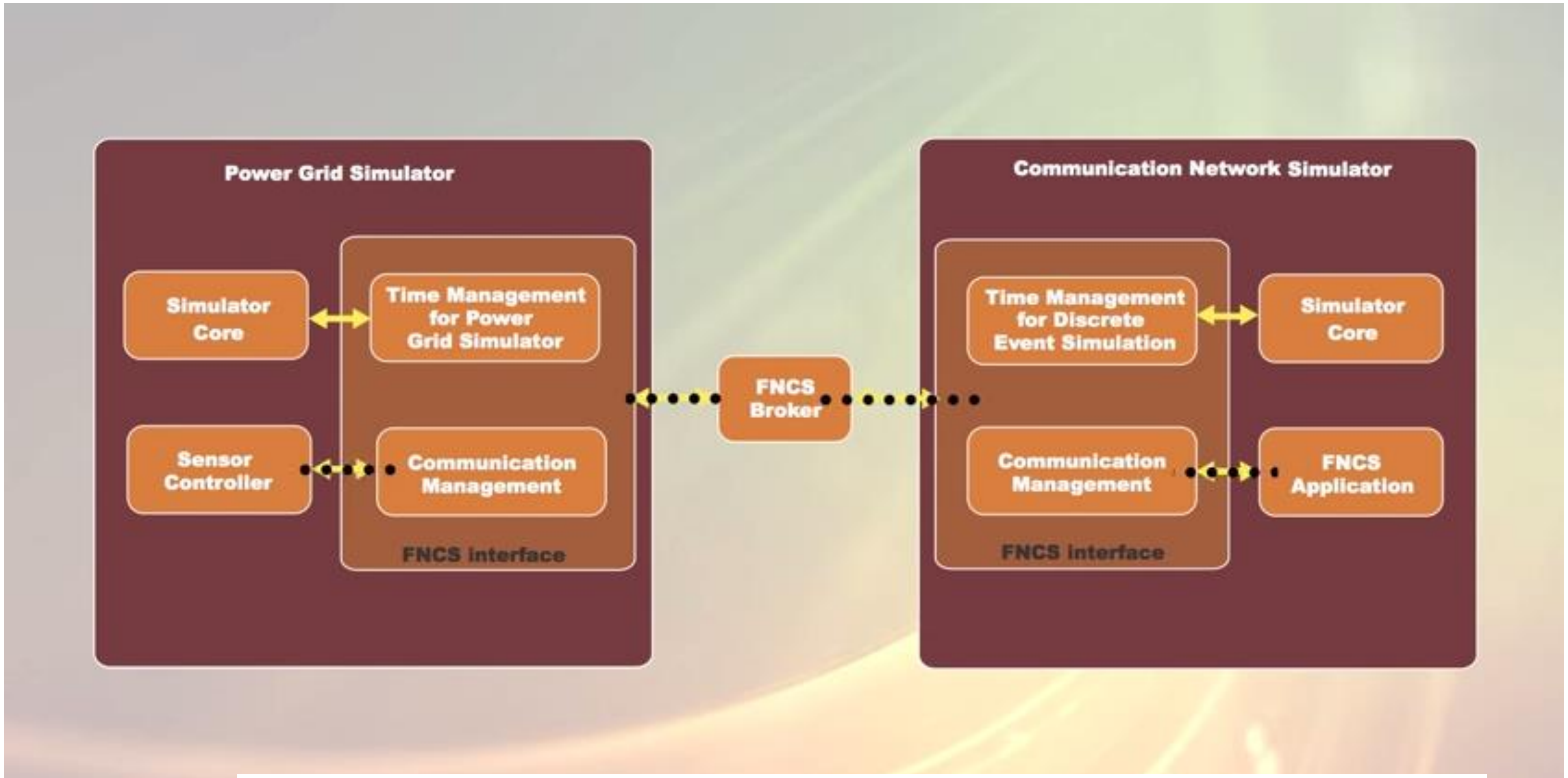


Image source: PNNLgov YouTube video:
Introducing FNCS: Framework for Network Co-Simulation

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FAQs

- Does ns-3 have a Windows version?
  - Yes, for Visual Studio 2012
  - http://www.nsnam.org/wiki/Ns-3_on_Visual_Studio_2012
- Does ns-3 support Eclipse or other IDEs?
  - Instructions have been contributed by users
  - http://www.nsnam.org/wiki/HOWTO_configure_Eclipse_with_ns-3
- Is ns-3 provided in Linux or OS X package systems (e.g. Debian packages)?
  - Ubuntu/Debian packages for ns-3.17 release
- Does ns-3 support NRL protolib applications?
  - Not yet

Summarizing

- ns-3 models are written in C++ and compiled into libraries
  - Python bindings are optionally created
- ns-3 programs are C++ executables or Python programs that call the ns-3 public API and can call other libraries
- ns-3 is oriented towards the command-line
- ns-3 uses no domain specific language
- ns-3 is not compatible with ns-2

Finding documentation and code

Resources

Web site:

http://www.nsnam.org

Mailing lists:

https://groups.google.com/forum/#!forum/ns-3-users

http://mailman.isi.edu/mailman/listinfo/ns-developers

Wiki:

http://www.nsnam.org/wiki/

Tutorial:

http://www.nsnam.org/docs/tutorial/tutorial.html

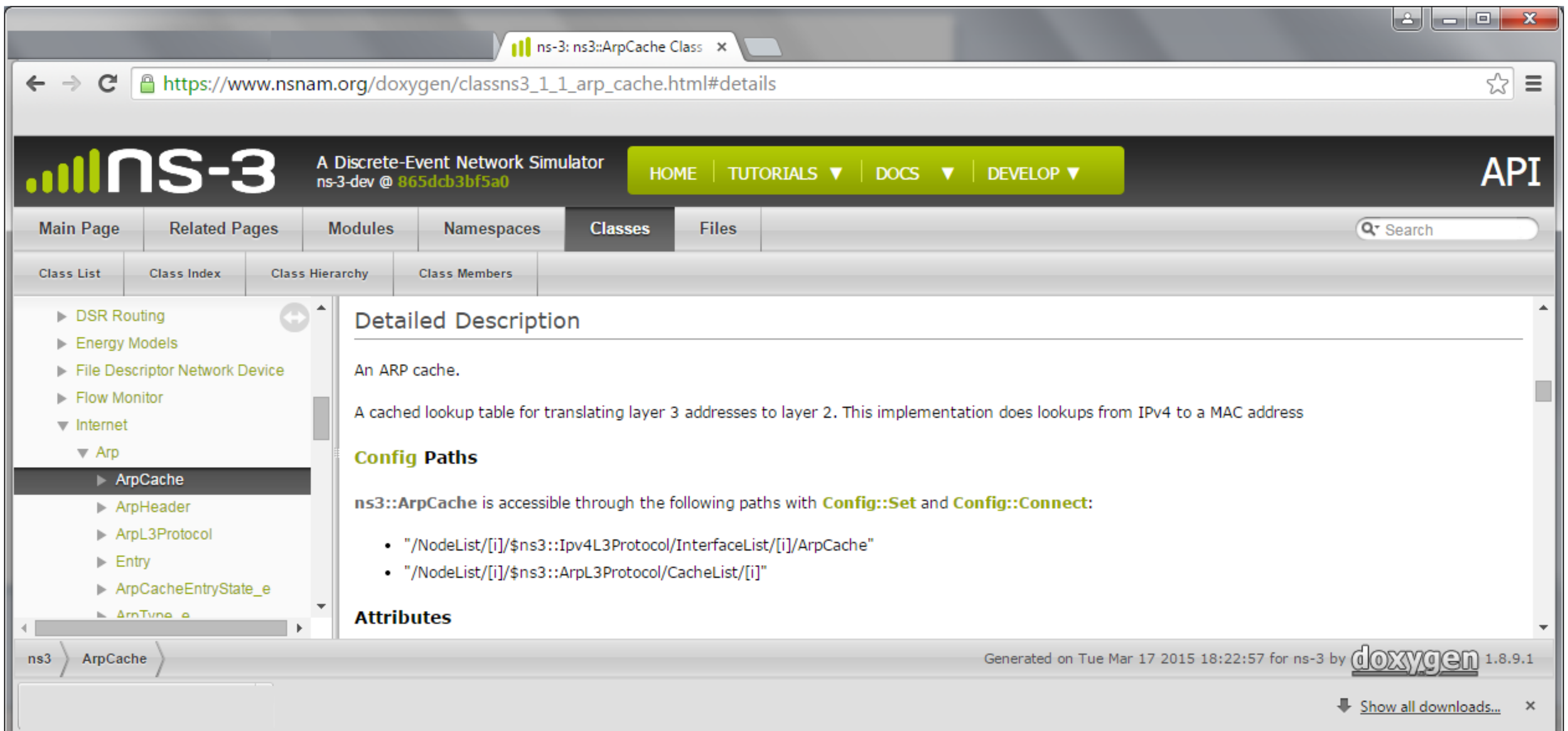
IRC: #ns-3 at freenode.net

Suggested steps

- Work through the ns-3 tutorial
- Browse the source code and other project documentation
  - manual, model library, Doxygen, wiki
  - ns-3 Consortium tutorials (May 2014)
    - https://www.nsnam.org/consortium/activities/training/
- Ask on ns-3-users mailing list if you still have questions
  - We try to answer most questions

APIs

- Most of the ns-3 API is documented with Doxygen
  - https://www.nsnam.org/doxygen



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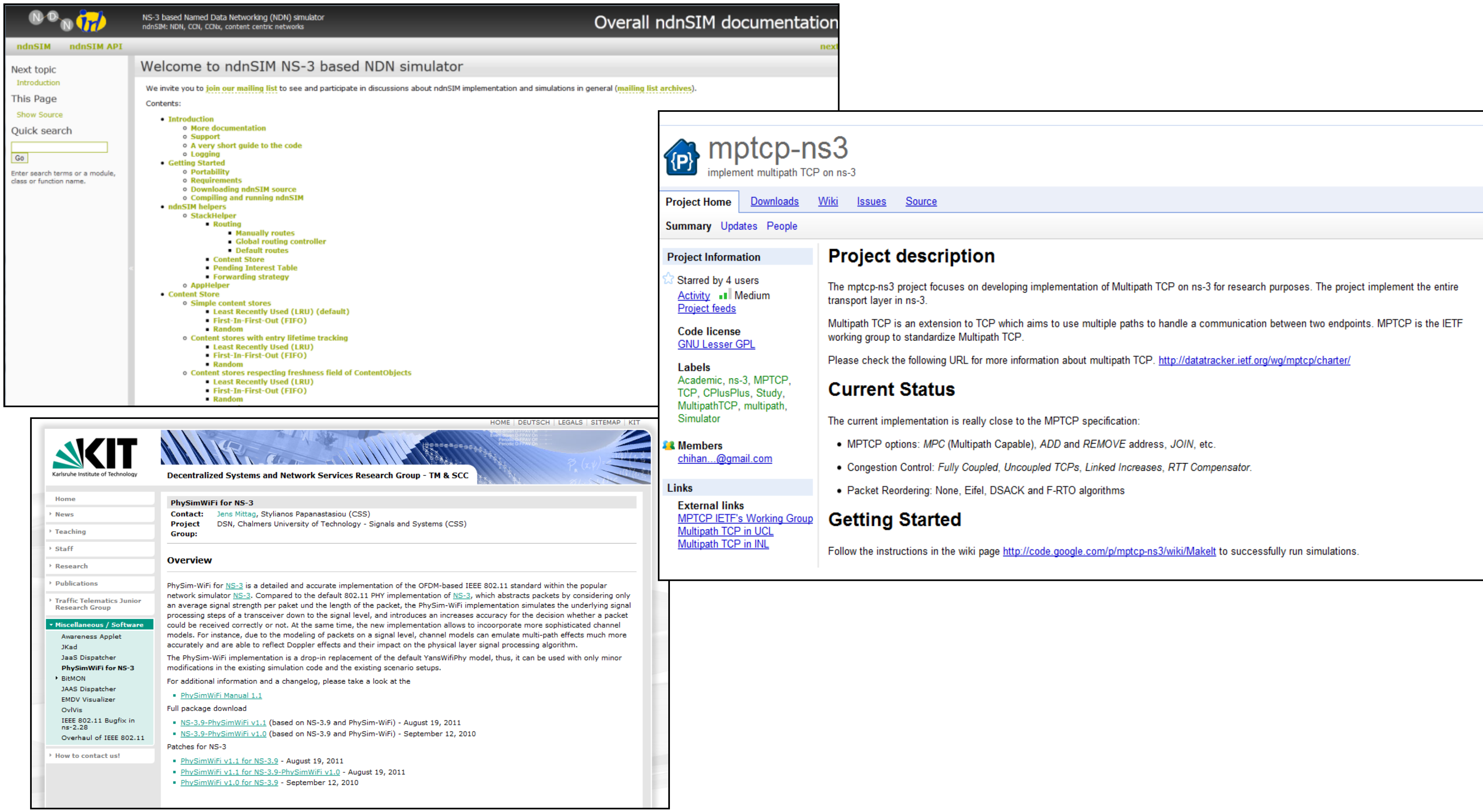
Contributed code and associated projects



Reading existing code

- Much insight can be gained from reading ns-3 examples and tests, and running them yourselves
- Many core features of ns-3 are only demonstrated in the core test suite (src/core/test)
- Stepping through code with a debugger is informative
  - callbacks and templates make it more challenging than usual

ns-3 build systems

Software introduction

- Download the latest release
  - `wget http://www.nsnam.org/releases/ns-allinone-3.19.tar.bz2`
  - `tar xjf ns-allinone-3.19.tar.bz2`
- Clone the latest development code
  - `hg clone http://code.nsnam.org/ns-3-allinone`

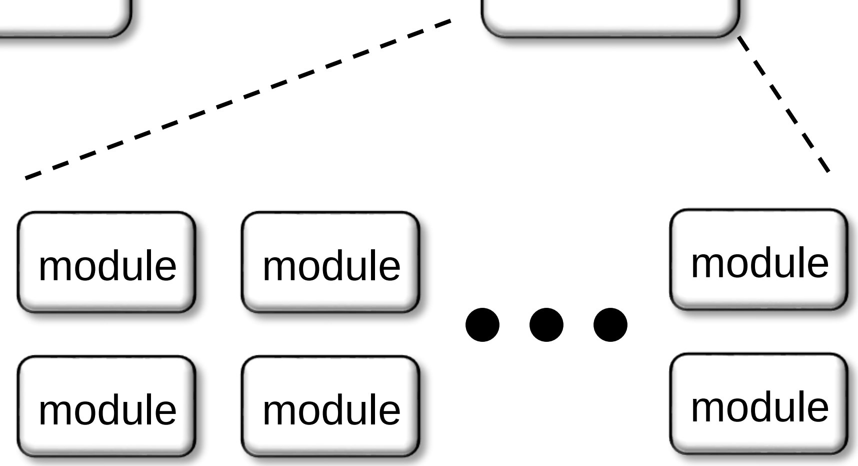
Q. What is "**hg clone**"?
A. Mercurial (http://www.selenic.com) is our source code control tool.

Software building

- Two levels of ns-3 build

1) bake (a Python-based build system to control an ordered build of ns-3 and its libraries)

2) waf, a build system written in Python



3) build.py (a custom Python build script to control an ordered build of ns-3 and its libraries) **<--- may eventually be deprecated**

ns-3 uses the 'waf' build system

- Waf is a Python-based framework for configuring, compiling and installing applications.
  - It is a replacement for other tools such as Autotools, Scons, CMake or Ant
  - http://code.google.com/p/waf/
- For those familiar with autotools:
- `configure` → `./waf configure`
- `make` → `./waf build`

waf configuration

- Key waf configuration examples

```
./waf configure
    --enable-examples
    --enable-tests
    --disable-python
    --enable-modules
```

- Whenever build scripts change, need to reconfigure

Demo: `./waf --help`
`./waf configure --enable-examples --enable-tests --enable-modules='core'`

Look at: `build/c4che/_cache.py`

wscript example

```
## -*- Mode: python; py-indent-offset: 4; indent-tabs-mode: nil; coding: utf-8; -*-

def build(bld):
    obj = bld.create_ns3_module('csma', ['network', 'applications'])
    obj.source = [
        'model/backoff.cc',
        'model/csma-net-device.cc',
        'model/csma-channel.cc',
        'helper/csma-helper.cc',
        ]
    headers = bld.new_task_gen(features=['ns3header'])
    headers.module = 'csma'
    headers.source = [
        'model/backoff.h',
        'model/csma-net-device.h',
        'model/csma-channel.h',
        'helper/csma-helper.h',
        ]

    if bld.env['ENABLE_EXAMPLES']:
        bld.add_subdirs('examples')

    bld.ns3_python_bindings()
```

waf build

- Once project is configured, can build via `./waf build` or `./waf`
- waf will build in parallel on multiple cores
- waf displays modules built at end of build

Demo: `./waf build`

Look at: `build/` libraries and executables

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Running programs

- `./waf shell` provides a special shell for running programs
  - Sets key environment variables

```
./waf --run sample-simulator
./waf --pyrun src/core/examples/sample-
  simulator.py
```

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Build variations

- Configuring a build type is done at waf configuration time
- debug build (default): all asserts and debugging code enabled

```
./waf -d debug configure
```

- optimized

```
./waf -d optimized configure
```

- static libraries

```
./waf --enable-static configure
```

Controlling the modular build

- One way to disable modules:
  - `./waf configure --enable-modules='a','b','c'`
- The `.ns3rc` file (found in utils/ directory) can be used to control the modules built
- Precedence in controlling build
  1) command line arguments
  2) .ns3rc in ns-3 top level directory
  3) .ns3rc in user's home directory

Demo how .ns3rc works

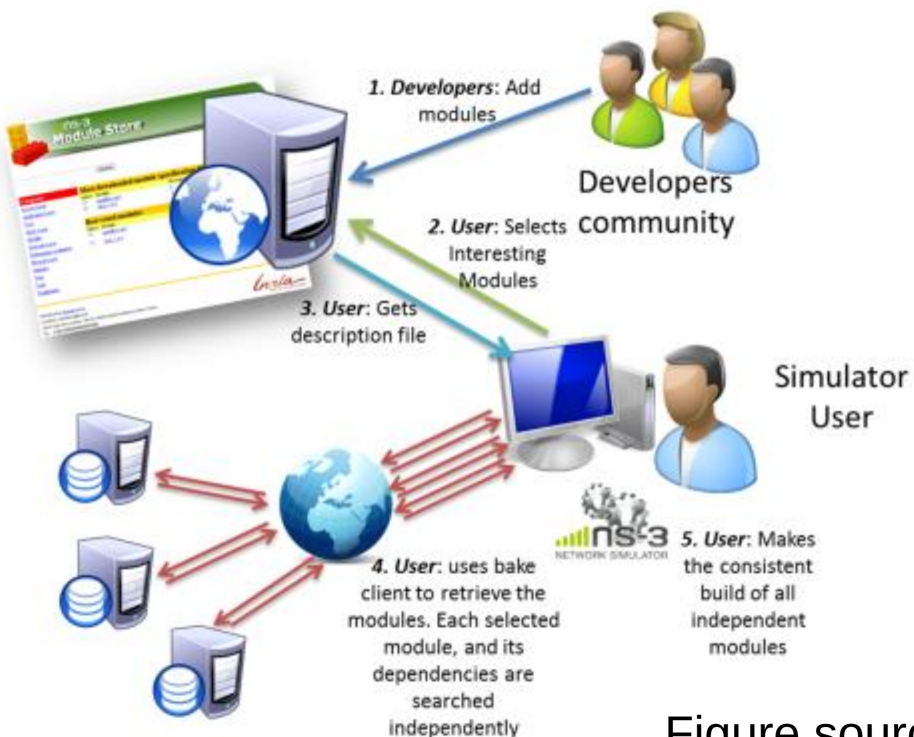
Building without wscript

- The scratch/ directory can be used to build programs without wscripts

Demo how programs can be built without wscripts

bake overview

- Open source project maintains a (more stable) core
- Models migrate to a more federated development process



"bake" tool (Lacage and Camara)

Components:

- build client
- "module store" server
- module metadata

Figure source: Daniel Camara

bake basics

- bake can be used to build the Python bindings toolchain, Direct Code Execution, Network Simulation Cradle, etc.
- Manual available at https://www.nsnam.org/docs/bake/tutorial/html/index.html

```
./bake.py configure -e <module>
./bake.py show
./bake.py download
./bake.py build
```

Placeholder slide for demoing bake

Demo: `./waf build`

Look at: `build/` libraries and executables

Visualization

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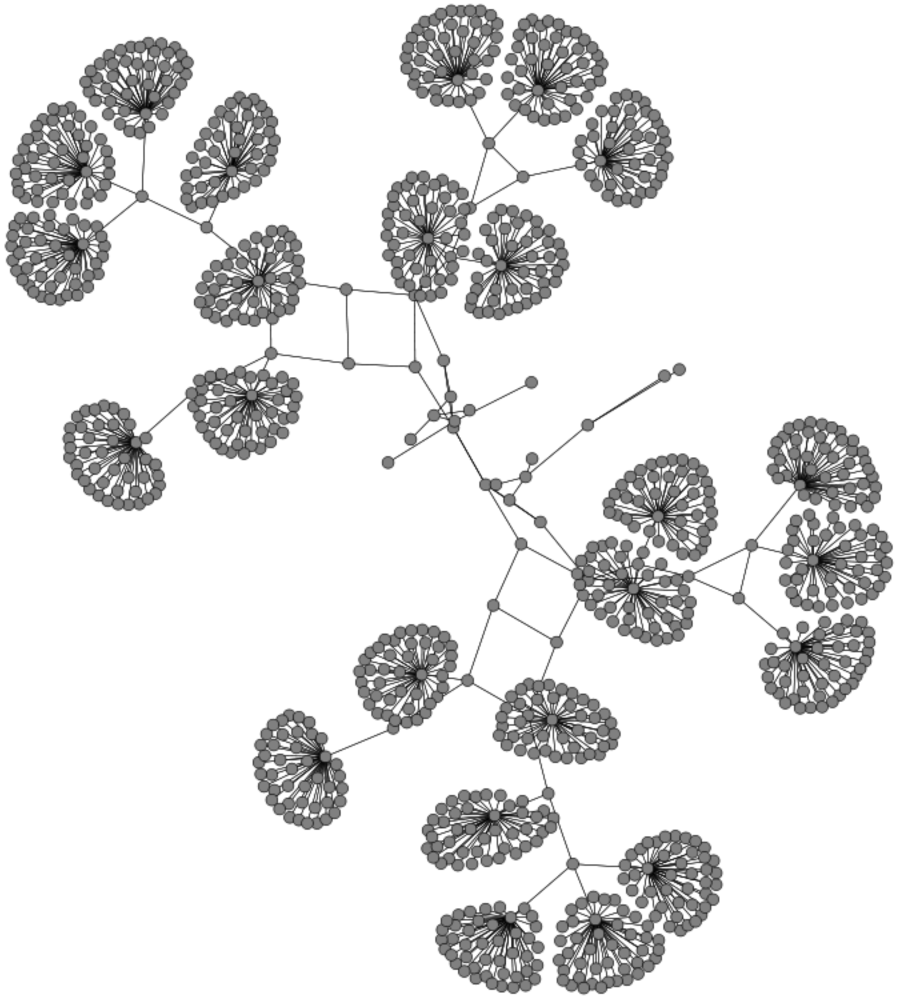
PyViz overview

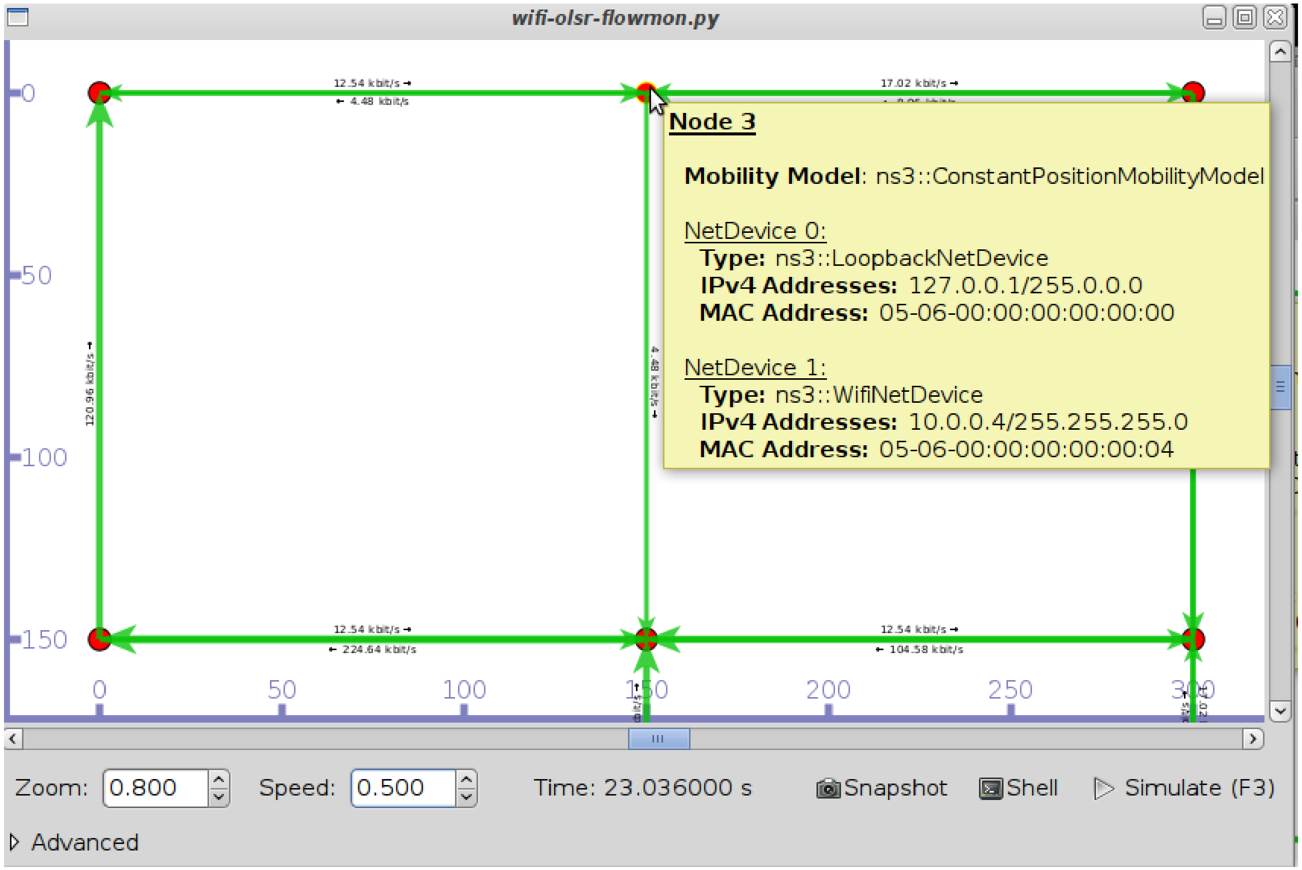
- Developed by Gustavo Carneiro
- Live simulation visualizer (no trace files)
- Useful for debugging
  - mobility model behavior
  - where are packets being dropped?
- Built-in interactive Python console to debug the state of running objects
- Works with Python and C++ programs

Pyviz screenshot (Graphviz layout)



Pyviz and FlowMonitor

- src/flow-monitor/examples/wifi-olsr-flowmon.py



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Enabling PyViz in your simulations

- Make sure PyViz is enabled in the build

```
SQlite stats data output      : not enabled (library 'sqlite3' not found)
Tap Bridge                    : enabled
PyViz visualizer              : enabled
Use sudo to set suid bit      : not enabled (option --enable-sudo not selected)
```

- If program supports CommandLine parsing, pass the option

```
--SimulatorImplementationType=
ns3::VisualSimulatorImpl
```

- Alternatively, pass the "--vis" option

FlowMonitor

- Network monitoring framework found in `src/flow-monitor/`
- Goals:
  - detect all flows passing through network
  - stores metrics for analysis such as bitrates, duration, delays, packet sizes, packet loss ratios

G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor architecture

- Basic classes
  - FlowMonitor
  - FlowProbe
  - FlowClassifier
  - FlowMonitorHelper
- IPv6 coming in ns-3.20 release

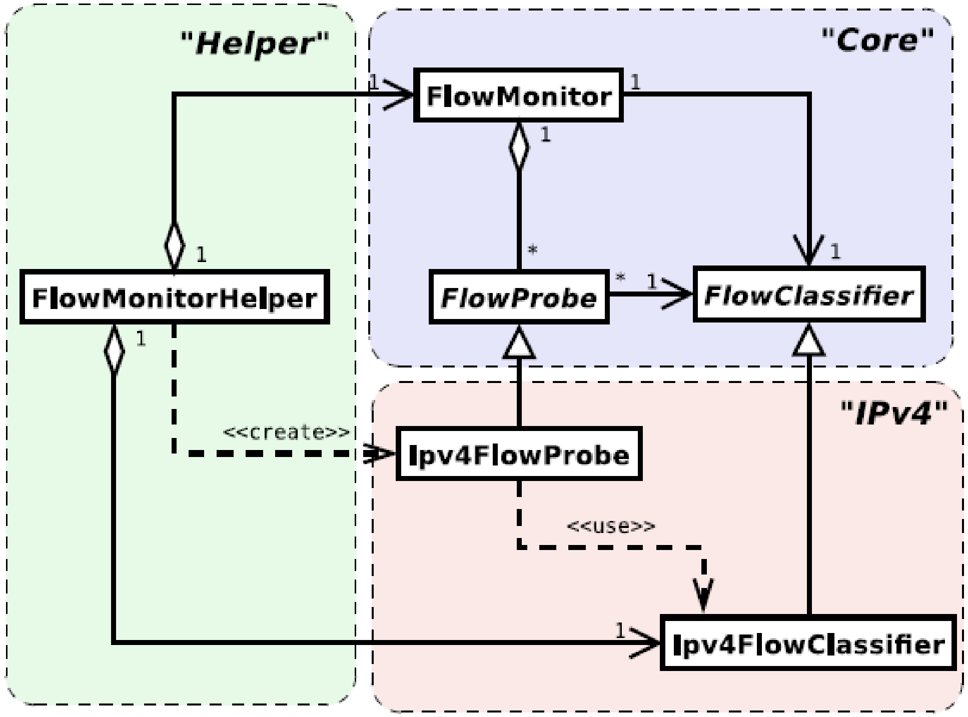
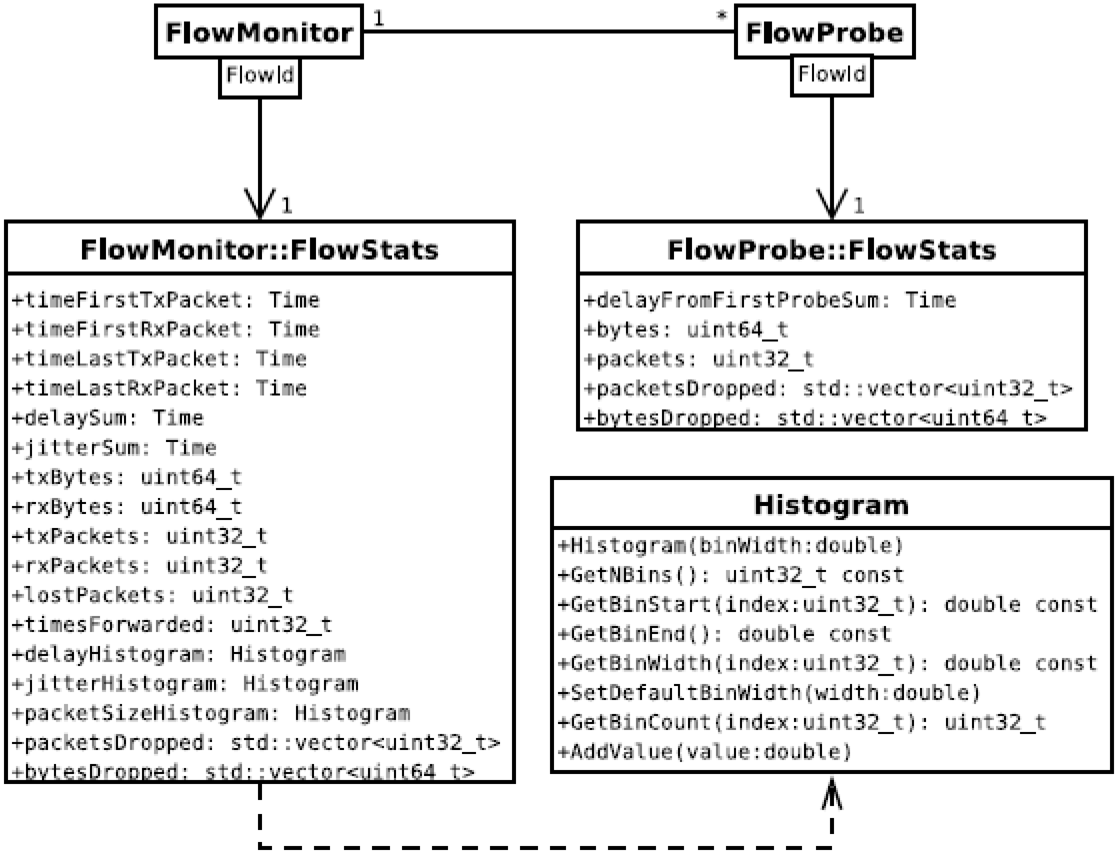


Figure credit: G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor statistics

- Statistics gathered



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FlowMonitor configuration

- `example/wireless/wifi-hidden-terminal.cc`

```
// 8. Install FlowMonitor on all nodes
FlowMonitorHelper flowmon;
Ptr<FlowMonitor> monitor = flowmon.InstallAll ();

// 9. Run simulation for 10 seconds
Simulator::Stop (Seconds (10));
Simulator::Run ();

// 10. Print per flow statistics
monitor->CheckForLostPackets ();
Ptr<Ipv4FlowClassifier> classifier = DynamicCast<Ipv4FlowClassifier> (flowmon.GetClassifier ());
std::map<FlowId, FlowMonitor::FlowStats> stats = monitor->GetFlowStats ();
for (std::map<FlowId, FlowMonitor::FlowStats>::const_iterator i = stats.begin (); i != stats.end (); ++i)
  {
    // first 2 FlowIds are for ECHO apps, we don't want to display them
    if (i->first > 2)
      {
        Ipv4FlowClassifier::FiveTuple t = classifier->FindFlow (i->first);
        std::cout << "Flow " << i->first - 2 << " (" << t.sourceAddress << " -> " << t.destinationAddress << ")\n";
        std::cout << "  Tx Bytes:   " << i->second.txBytes << "\n";
        std::cout << "  Rx Bytes:   " << i->second.rxBytes << "\n";
        std::cout << "  Throughput: " << i->second.rxBytes * 8.0 / 10.0 / 1024 / 1024  << " Mbps\n";
      }
  }
```

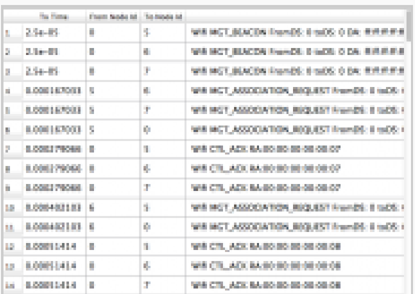
FlowMonitor output

- This program exports statistics to stdout
- Other examples integrate with PyViz

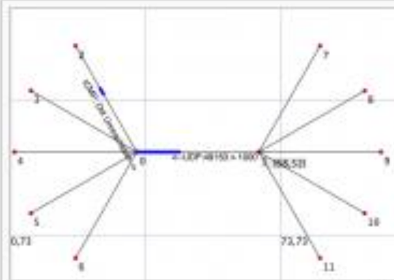
```
Hidden station experiment with RTS/CTS disabled:
Flow 1 (10.0.0.1 -> 10.0.0.2)
  Tx Bytes:   3847500
  Rx Bytes:   316464
  Throughput: 0.241443 Mbps
Flow 2 (10.0.0.3 -> 10.0.0.2)
  Tx Bytes:   3848412
  Rx Bytes:   336756
  Throughput: 0.256924 Mbps
------------------------------------------------
Hidden station experiment with RTS/CTS enabled:
Flow 1 (10.0.0.1 -> 10.0.0.2)
  Tx Bytes:   3847500
  Rx Bytes:   306660
  Throughput: 0.233963 Mbps
Flow 2 (10.0.0.3 -> 10.0.0.2)
  Tx Bytes:   3848412
  Rx Bytes:   274740
  Throughput: 0.20961 Mbps
```

NetAnim

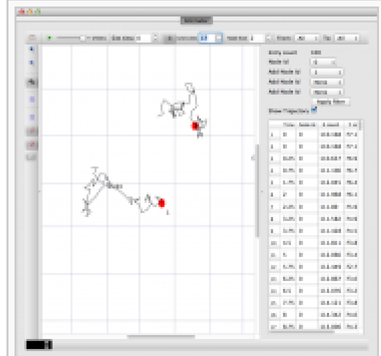
- "NetAnim" by George Riley and John Abraham



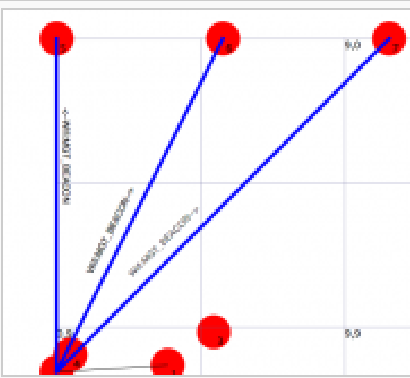
Packet Statistics



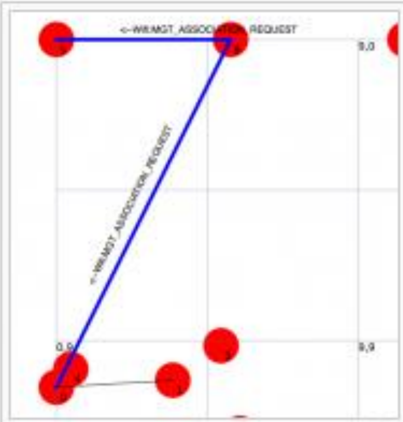
Dumbbell



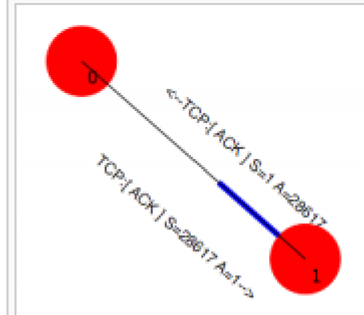
Node Trajectory



Wifi Beacon



Wifi Assoc



TCP flags

NetAnim key features

- Animate packets over wired-links and wireless-links
  - limited support for LTE traces
- Packet timeline with regex filter on packet meta-data.
- Node position statistics with node trajectory plotting (path of a mobile node).
- Print brief packet-meta data on packets

Placeholder for netanim videos