Network simulation using ns-3

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Chapter 4: conceptual overview

Source material:

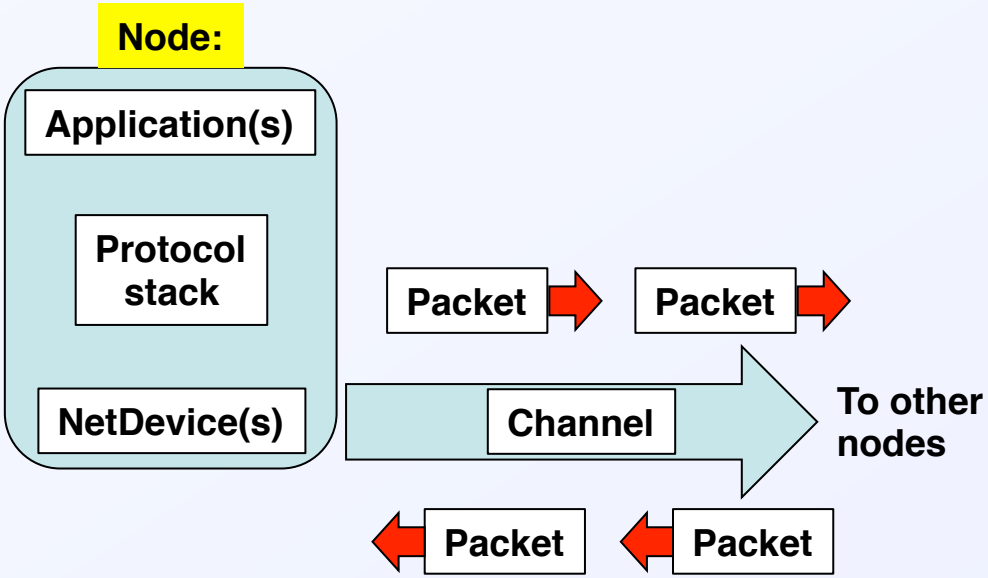
- Online tutorial: http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html#conceptual-overview
- M. Lacage (2009): http://inl.info.ucl.ac.be/tutorials/tfiss09-lacage
- G. Riley (2008): http://www.wns2.org/docs/wns_tutorial-handout.pdf
- Christhu raj M. R., "A Comprehensive Overview of Different Network Simulators", IJET 5, 325-332 (2013)
- T. Predojev (2012): http://wikienergy.cttc.es/images/2/2d/ns-3-tutorial-complete.pdf
- E. K. Cetinkaya and J. P. G. Sterbenz (2011): http://www.ittc.ku.edu/~jpgs/courses/mwnets/lecture-lab-intro2ns-3-display.pdf

Why simulate?

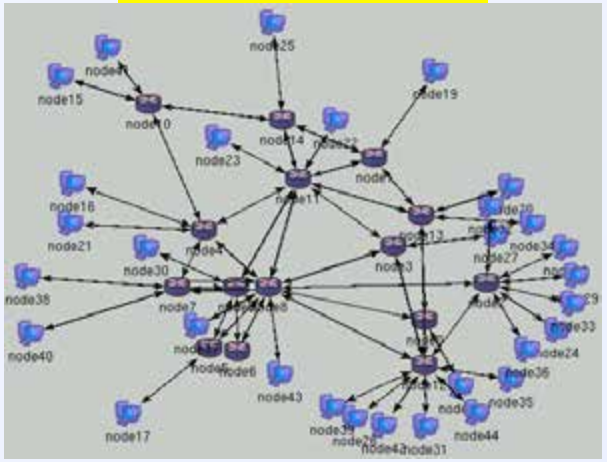
- Arguments against simulation
  - Simulation will never be as good as real thing
  - PC's are cheap and getting cheaper ⇒ test bed experiments
- Arguments for simulation
  - Reproducibility
  - Easier to set up, deploy, maintain
  - Can investigate things that do not yet exist
  - Can scale to larger problem size

Best is combination of real test beds + simulation

What are we actually simulating?



Network topology:



- Nodes: hosts, routers, servers,…
- Applications: generate and consume traffic in network
- Protocols: broker connections, access, addressing, routing,…
- NetDevices: e.g., ethernet & wireless cards
- Channels: transmission medium (cable, EM waves,…)
- Packets: make up network traffic

Are there some network simulators out there?

Quite a few actually, for ex:

NS-2

J-Sim

TOSSIM

GloMoSim

Agent J

SHARPE

OPNET

Netsim

ns-3

Qual Net

SPNP

OMNET++

INSANE

TrSim

Query Cycle

Maisie

Neurogrid

We will focus on ns-3

What is ns-3? What makes it special?

- Discrete event simulator
  - Events model packet transmission, receipt, timers, etc…
  - Events are maintained in time-ordered events list
- Aimed at research and education
- Written entirely in C++ (single language ⇒ easier to debug user code)
- Open-source ⇒ many contributors/maintainers ⇒ longevity of the project
- Models are close to real world
  - Easier to execute real-life codes
  - Can interact with real-world packets
  - Aligned with input/output standards (pcap traces)
- Modular and well-documented

Installing ns-3

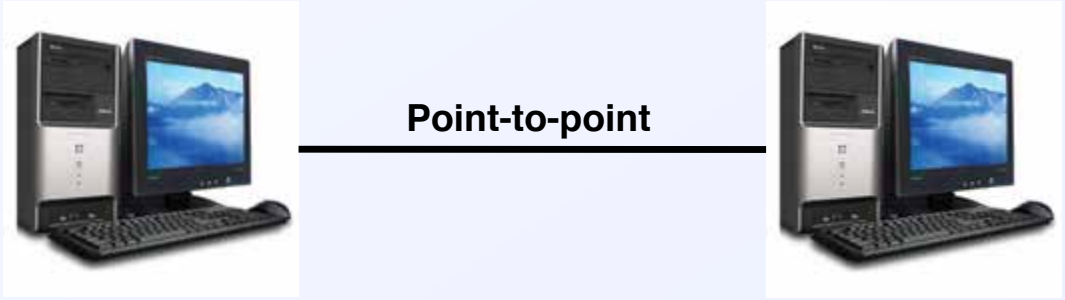
- Getting ns-3
  - Retrieve from repos using Mercurial:
    - `$ hg clone http://code.nsnam.org/ns-3-allinone`
    - `$ ./download.py -n ns-3-dev`
  - Or: download tarballs from http://www.nsnam.org/releases/
- Building/Installing ns-3
  - Uses `waf` build tool instead of `configure` and `make`
    - `$ ./waf -d debug –enable-examples –enable-tests configure`
    - `$ ./waf`
  - Detailed directions: http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html#building-ns-3

Structure of a generic ns-3 script

- Boilerplate: important for documentation
- Module includes: include header files
- ns-3 namespace: global declaration
- Logging: optional
- Main function: declare main function
- Topology helpers: objects to combine distinct operations
- Applications: on/off, UdpEchoClient/Server
- Tracing: `.tr` and/or `.pcap` files
- Simulator: start/end simulation, cleanup

Let's write a first network simulation

- A word about programming languages
  - I'll use C/C++, but also possible to use python
- Let's simulate a simple dumbbell topology:



- You will see a lot of container and helper classes
  - Containers are a convenient way of creating, managing, accessing groups of similar objects
  - Helpers make life easier by providing higher-level commands to execute common pieces of code

Containers and Helpers

- The general idea
  - Sets of objects are stored in Containers
  - Operations encoded in Helper object, apply to Container
- Provide high-level wrappers
- Easy way to build network models with repeating patterns of components, configurations
- With helpers, model description is
  - High level
  - More readable

Examples

- Containers
  - `NodeContainer`
  - `NetDeviceContainer`
  - `Ipv4AddressContainer`
- Helper classes
  - `InternetStackHelper`
  - `WifiHelper`
  - `MobilityHelper`
  - `OlsrHelper`
- Many models provides a helper class
  - See files in `src/*/helper` for source code

We will see examples in the various tutorial scripts

The C++ program that does the work: examples/tutorial/first.cc

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

Omitted boilerplate legalese at the top of the code to save space, but read it!

No need to squint: we're going to look at this in detail!

Focus first on the lines that create the network topology

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
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```

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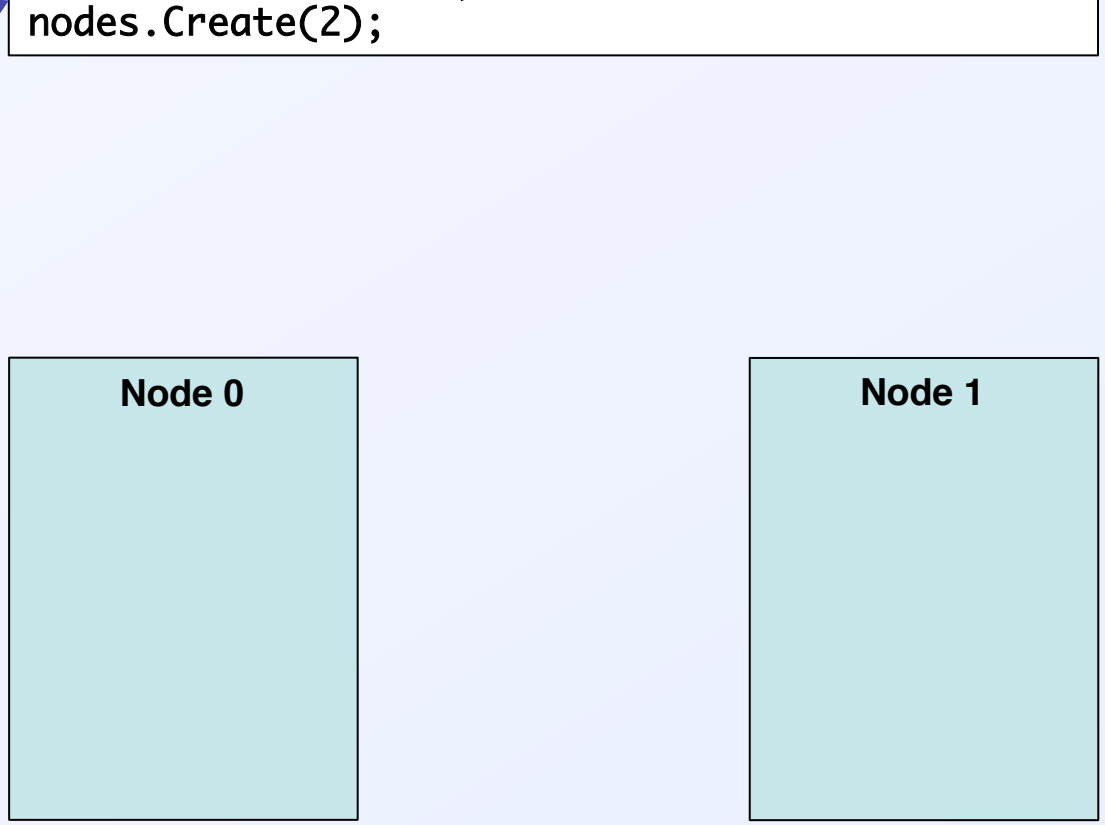

These nodes don't do anything yet

Next, define the point-to-point channel

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
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  Simulator::Run ();
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  return 0;
}
```

```
PointToPointHelper pointToPoint;
pointToPoint.SetDeviceAttribute ("DataRate",
  StringValue     ("5Mbps"));
pointToPoint.SetChannelAttribute ("Delay",
  StringValue ("2ms"));
```

point-to-point channel

We've created the channel, but it's not connected to anything yet

Next, define the point-to-point channel

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
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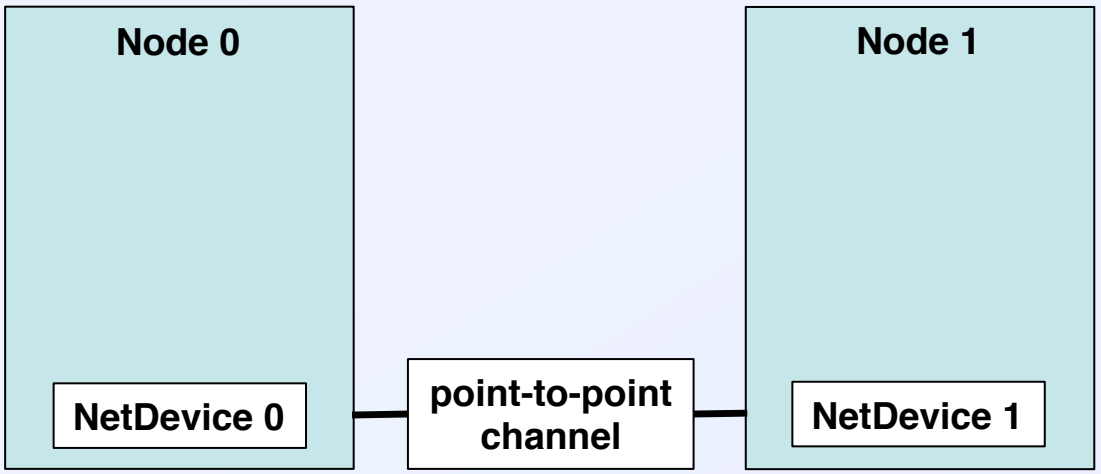
  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
NetDeviceContainer devices;
devices = pointToPoint.Install (nodes);
```



We've installed NICs on the nodes, and linked them via the p2p channel

Let's define IP addresses

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
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  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");
```

- Mask = 255.255.255.0
- 1st address = 10.1.1.1
- 2nd address = 10.1.1.2
- …

Now we assign the IP addresses

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
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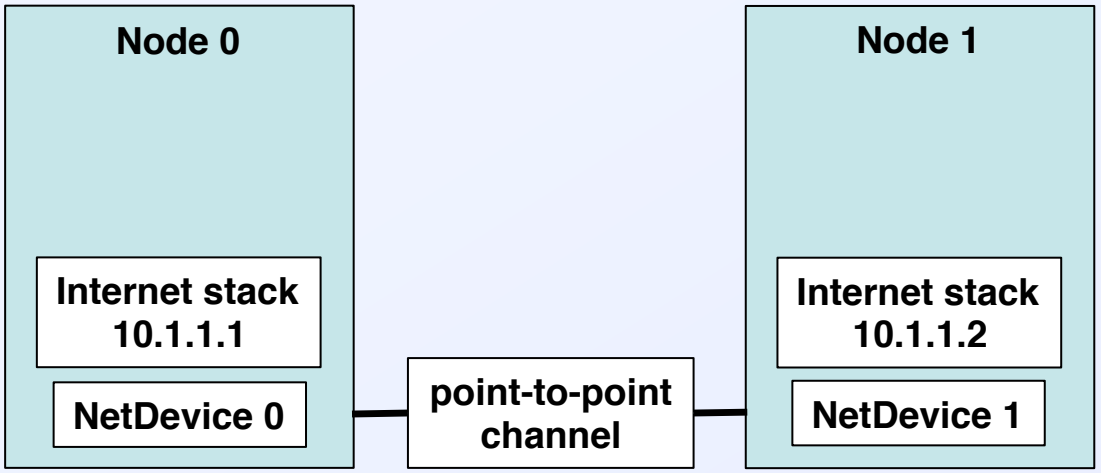

All we need now are applications to generate some traffic

Set up the server application

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
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  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
UdpEchoServerHelper echoServer (9);
```

- Sets up User Datagram Protocol echo server
- Uses port 9
- Echo server just echoes back any packet it receives
  - used, e.g., for testing or troubleshooting

Install the server application

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
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```

```
ApplicationContainer serverApps =
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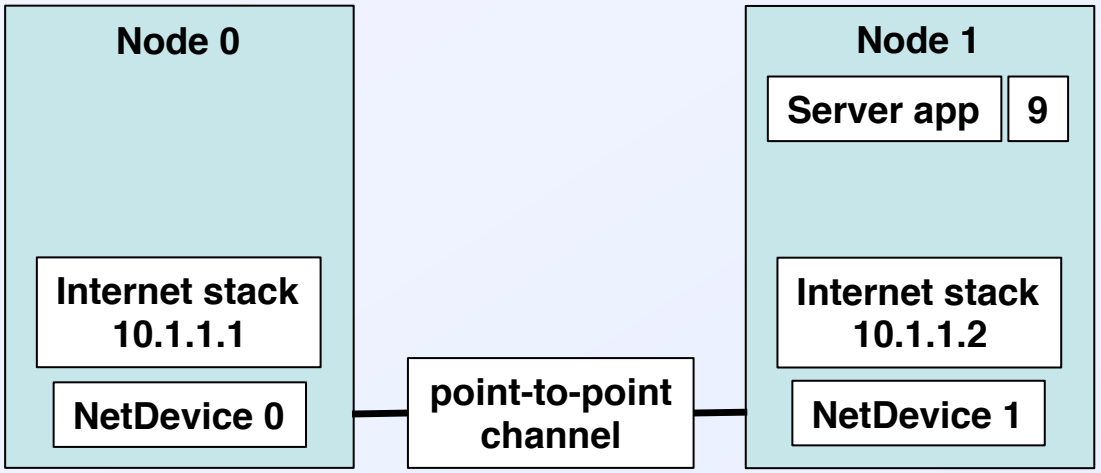
```



Schedule the server activity

```
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  Simulator::Run ();
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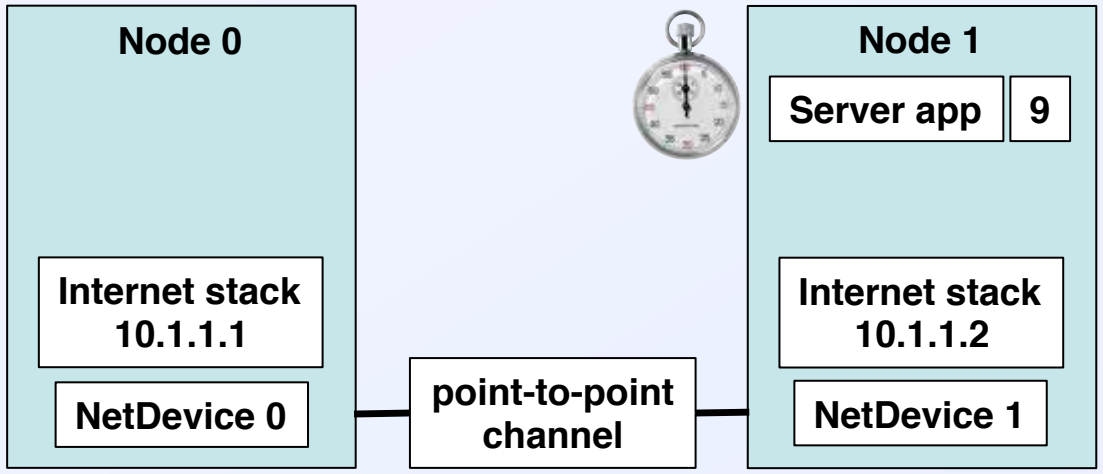
  return 0;
}
```

```
serverApps.Start (Seconds (1.0));
serverApps.Stop (Seconds (10.0));
```

- Echo server enabled at t = 1s
- Echo server disabled at t = 10s



Now the server knows when to listen: who's going to talk to it?

Define the client application

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
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  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
UdpEchoClientHelper echoClient
  (interfaces.GetAddress (1), 9);
```

- Remote address = server's IP = 10.1.1.2
- Remote port = 9

```
echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
echoClient.SetAttribute ("PacketSize", UintegerValue (1024));
```

- MaxPackets = max number of packets to send
- Interval = time between sent packets
- PacketSize = size (1024 bytes in this case)

Install the client application

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

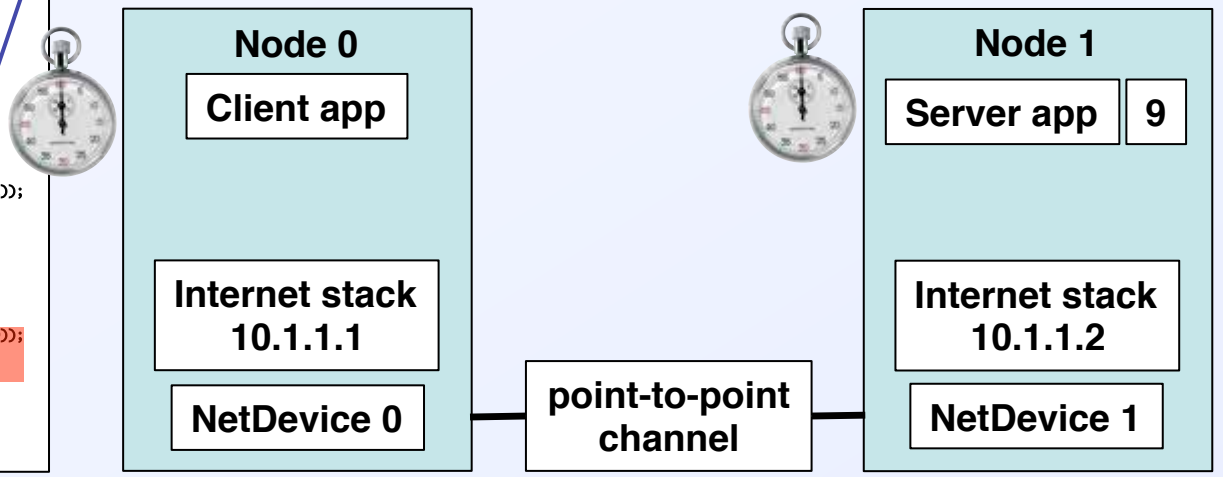
  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
ApplicationContainer clientApps =
  echoClient.Install (nodes.Get (0));
clientApps.Start (Seconds (2.0));
clientApps.Stop (Seconds (10.0));
```



Client: at t = 2s send a packet to the server

Finally: run the simulation & clean up

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
Simulator::Run
();
```

- Run the simulation (duh!)

```
Simulator::Destroy ();
return 0;
```

- Clean up

What about output?

Logging

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");
```

```
LogComponentEnable ("UdpEchoClientApplication",
  LOG_LEVEL_INFO);
LogComponentEnable ("UdpEchoServerApplication",
  LOG_LEVEL_INFO);
```

Now traffic activity will be printed to the console

Some standard overhead

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"
```

```
using namespace ns-3;
```

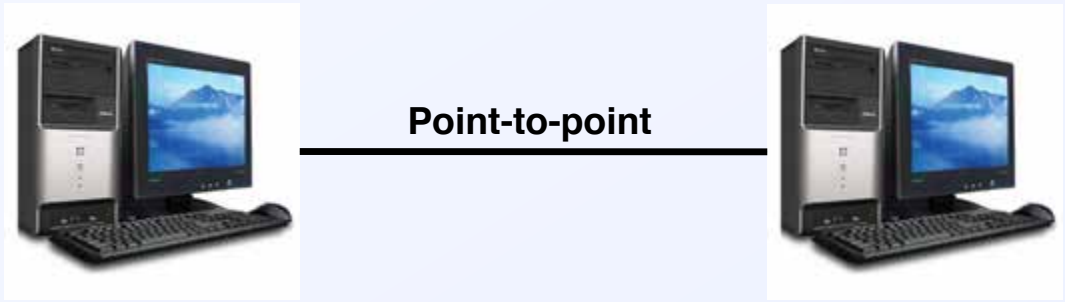
Building and running the script

- Copy `examples/tutorial/first.cc` into the `scratch` directory
  - `$ cp examples/tutorial/first.cc scratch/myfirst.cc`
- Build your script using WAF
  - `$ ./waf`
- Run it out of the scratch directory
  - `$ ./waf –run scratch/myfirst`
- Output:

```
Waf: Entering directory `/mypath/ns-3-dev/build'
Waf: Leaving directory `/mypath/ns-3-dev/build'
'build' finished successfully (5.283s)
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.1.2
```

Closer look at the output from the script

```
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.1.2
```



- Pretty terse output: can we get more?
  - Who did the sending & receiving?
  - Event times?
  - More…
- What if we want more than 2 nodes?

Now that you've had your first taste of ns-3: what else is there?

- Getting info out of your script
  - For debugging: logging
  - For actual work: tracing (we'll spend plenty of time on this)
- Building topologies
- Models, attributes and reality
- Where to go for more info
  - Official tutorial: http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html
  - Doxygen: http://www.nsnam.org/docs/release/3.17/doxygen/index.html
  - Forum: https://groups.google.com/forum/?fromgroups#!forum/ns-3-users
  - Mathieu Lacage video (philosophy and design of ns-3): http://inl.info.ucl.ac.be/tutorials/tfiss09-lacage

Chapter 5: Tweaking

Source material:

- Online tutorial: http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html#tweaking
- M. Lacage (2009): http://www.nsnam.org/tutorials/ns-3-tutorial-tunis-apr09.pdf

Logging

- Not the same thing as tracing
- Used primarily for
  - Quick messages
  - Debugging, not meant for extracting results!
- Macros of the form "NS_LOG*"
- Define logging component for your script
  - NS_LOG_COMPONENT_DEFINE(…)
  - Enable logging for the script
  - LogComponentEnable(…)
  - Disable logging for the script
  - LogComponentDisable(…)

Different logging levels for different levels of verbosity

- Logging levels
  - `NS_LOG_ERROR(…)`: serious error messages only
  - `NS_LOG_WARN(…)`: warning messages
  - `NS_LOG_DEBUG(…)`: rare ad-hoc debug messages
  - `NS_LOG_INFO(…)`: informational messages (e.g., banners)
  - `NS_LOG_FUNCTION(…)`: function tracing
  - ~~`NS_LOG_PARAM(…)`: parameters to function~~
  - `NS_LOG_LOGIC(…)`: control flow tracing within functions
  - `NS_LOG_UNCOND(…)`: always display, regardless of logging level
  - `NS_LOG_ALL(…)`: log everything
- Displaying log messages: two ways
  - In your script: `LogComponentEnable(…)`
  - Using the `NS_LOG` environment variable

Using the NS_LOG environment variable

- With NS_LOG you can
  - Turn logging on/off for specific components
  - Set logging level
- In general you do something like this:
  - `export NS_LOG="name_of_logging_component=logging_flag"`
    - Or `setenv NS_LOG …` if you're using csh
  - The logging_flag can be
    - A logging level (e.g., `level_all`)
    - A combination of flags OR-ed together to print more info
- To set logging levels for several components use ":" between components

Let's look at some examples

Let's go back to `first.cc`

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");
```

```
LogComponentEnable ("UdpEchoClientApplication",
  LOG_LEVEL_INFO);
LogComponentEnable ("UdpEchoServerApplication",
  LOG_LEVEL_INFO);
```

```
$ ./waf –run scratch/myfirst
```

```
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.1.2
```

How do we get more info out of the client app without recompiling?

Getting debugging info from the client application

```
$ setenv NS_LOG “UdpEchoClientApplication=level_all”
$ ./waf –run scratch/myfirst
```

```
UdpEchoClientApplication:UdpEchoClient()
UdpEchoClientApplication:SetDataSize(1024)
UdpEchoClientApplication:StartApplication()
UdpEchoClientApplication:ScheduleTransmit()
UdpEchoClientApplication:Send()
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
UdpEchoClientApplication:HandleRead(0x683d40, 0x6845c0)
Received 1024 bytes from 10.1.1.2
UdpEchoClientApplication:StopApplication()
UdpEchoClientApplication:DoDispose()
UdpEchoClientApplication:~UdpEchoClient()
```

Now we can see all the function calls made by the application
Next: who sent and received what?

Adding a prefix to logged messages

Use "|" to combine flags

Use ":" to separate multiple components

```
$ setenv NS_LOG "UdpEchoClientApplication=level_all|prefix_func:
  UdpEchoServerApplication=level_all|prefix_func"
$ ./waf -run scratch/myfirst
```

Don't use a newline here!

```
UdpEchoServerApplication:UdpEchoServer()
UdpEchoClientApplication:UdpEchoClient()
UdpEchoClientApplication:SetDataSize(1024)
UdpEchoServerApplication:StartApplication()
UdpEchoClientApplication:StartApplication()
UdpEchoClientApplication:ScheduleTransmit()
UdpEchoClientApplication:Send()
UdpEchoClientApplication:Send(): Sent 1024 bytes to 10.1.1.2
UdpEchoServerApplication:HandleRead(): Received 1024 bytes from 10.1.1.1
UdpEchoServerApplication:HandleRead(): Echoing packet
UdpEchoClientApplication:HandleRead(0x683d50, 0x6845d0)
UdpEchoClientApplication:HandleRead(): Received 1024 bytes from 10.1.1.2
UdpEchoClientApplication:StopApplication()
UdpEchoServerApplication:StopApplication()
UdpEchoClientApplication:DoDispose()
UdpEchoServerApplication:DoDispose()
UdpEchoClientApplication:~UdpEchoClient()
UdpEchoServerApplication:~UdpEchoServer()
```

Notice these lines

Who said what when? Extracting timing information

```
$ setenv NS_LOG "UdpEchoClientApplication=level_all|prefix_func|prefix_time:
   UdpEchoServerApplication=level_all|prefix_func|prefix_time"
$ ./waf -run scratch/myfirst
```

```
0s UdpEchoServerApplication:UdpEchoServer()
0s UdpEchoClientApplication:UdpEchoClient()
0s UdpEchoClientApplication:SetDataSize(1024)
1s UdpEchoServerApplication:StartApplication()
2s UdpEchoClientApplication:StartApplication()
2s UdpEchoClientApplication:ScheduleTransmit()
2s UdpEchoClientApplication:Send()
2s UdpEchoClientApplication:Send(): Sent 1024 bytes to 10.1.1.2
2.00369s UdpEchoServerApplication:HandleRead(): Received 1024 bytes from 10.1.1.1
2.00369s UdpEchoServerApplication:HandleRead(): Echoing packet
2.00737s UdpEchoClientApplication:HandleRead(0x6842a0, 0x684b20)
2.00737s UdpEchoClientApplication:HandleRead(): Received 1024 bytes from 10.1.1.2
10s UdpEchoClientApplication:StopApplication()
10s UdpEchoServerApplication:StopApplication()
UdpEchoClientApplication:DoDispose()
UdpEchoServerApplication:DoDispose()
UdpEchoClientApplication:~UdpEchoClient()
UdpEchoServerApplication:~UdpEchoServer()
```

Note the extra 3.69 ms: due to channel delay & device data rate

Adding your own log messages to the script

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

Add the line:
`NS_LOG_INFO("Creating Topology");`

```
$ setenv NS_LOG "FirstScriptExample=info"
$ ./waf -run scratch/myfirst
```

```
Creating Topology
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.1.2
```

Notice this line

A first (quick) look at tracing

- Tracing is a structured form of simulation output
- Built on the principle of trace sources and sinks
  - Trace source: signals sim event and provides access to the data
  - Trace sink: consumes the trace information
- For now: high-level tracing
  - Use pre-defined trace sinks in helpers
- Two types of tracing are available
  - ASCII tracing: produces readable files
  - PCAP tracing: produces files for traffic analyzers (tcpdump, wireshark)

Let's look at some examples

ASCII tracing in `myfirst.cc`

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

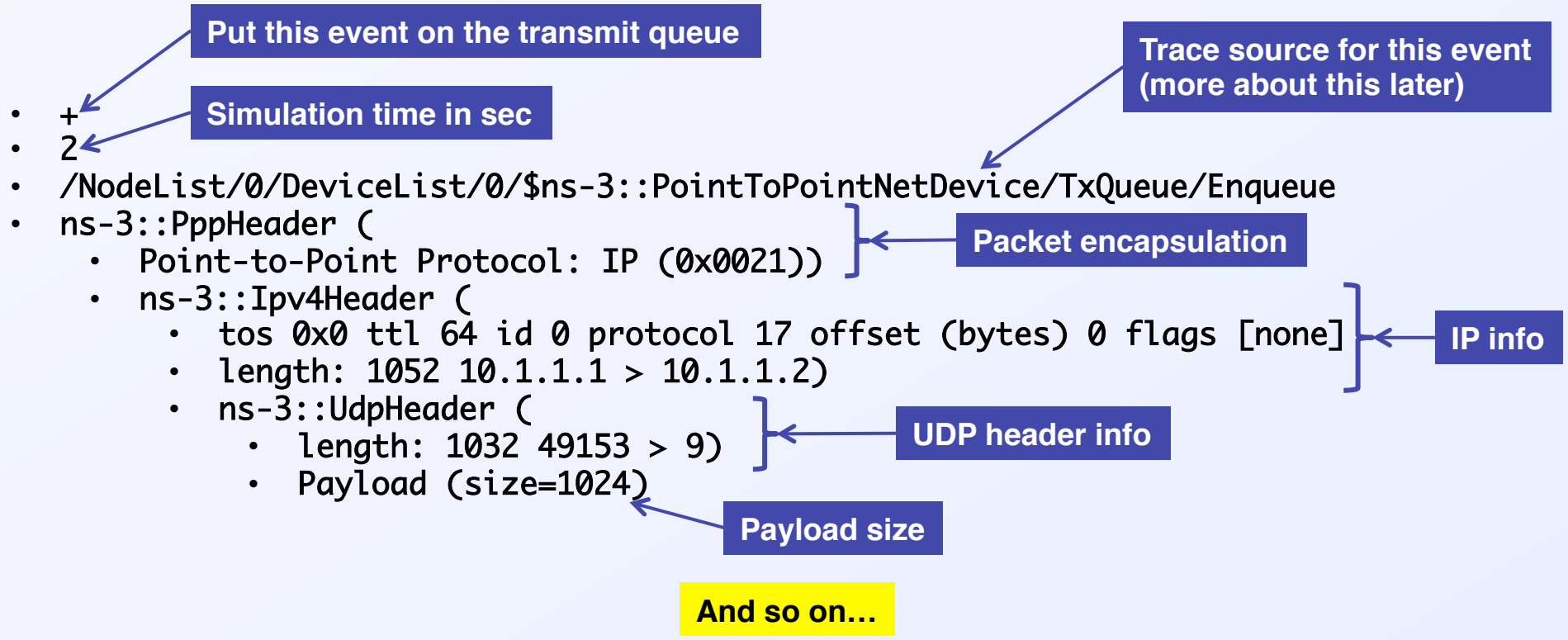
```
AsciiTraceHelper ascii;
pointToPoint.EnableAsciiAll( ascii.CreateFileStre
  am("myfirst.tr"));
```

```
$ ./waf –run scratch/myfirst
```

- **Creates `myfirst.tr` in top level directory**
- **Each line = one trace event**

The `myfirst.tr` file: breakdown of the 1st line

```
+2 /NodeList/0/DeviceList/0/$ns-3::PointToPointNetDevice/TxQueue/Enqueue
ns-3::PppHeader (Point-to-Point Protocol: IP (0x0021)) ns-3::Ipv4Header
(tos 0x0 ttl 64 id 0 protocol 17 offset (bytes) 0 flags [none] length:
1052 10.1.1.1 > 10.1.1.2) ns-3::UdpHeader (length: 1032 49153 > 9) Payload
(size=1024)
```



PCAP tracing in `myfirst.cc`

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);

  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer devices;
  devices = pointToPoint.Install (nodes);

  InternetStackHelper stack;
  stack.Install (nodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");

  Ipv4InterfaceContainer interfaces = address.Assign (devices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (nodes.Get (1));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.0)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

  ApplicationContainer clientApps = echoClient.Install (nodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

```
pointToPoint.EnablePcapAll("myfirst");
```

```
$ ./waf -run scratch/myfirst
```

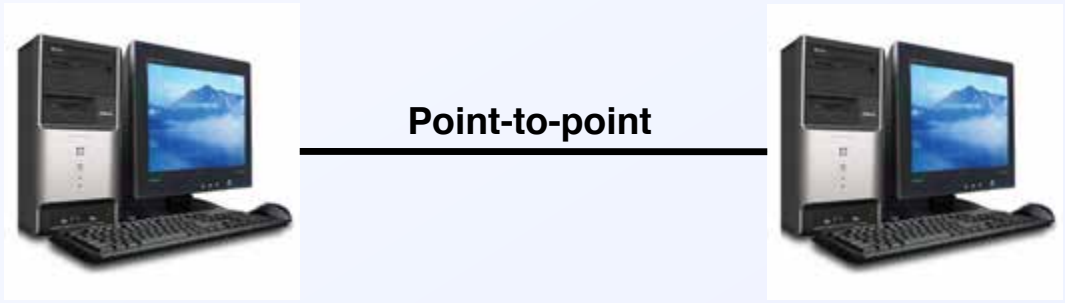
Creates pcap files in top level directory

- `myfirst-0-0.pcap`
- `myfirst-1-0.pcap`

node **device**

We'll see later how to give more descriptive names…

Contents of the PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r myfirst-0-0.pcap
reading from file myfirst-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.1.2.9: UDP, length 1024
2.007372 IP 10.1.1.2.9 > 10.1.1.1.49153: UDP, length 1024
```

```
$ /usr/sbin/tcpdump -nn -tt -r myfirst-1-0.pcap
reading from file myfirst-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.1.2.9: UDP, length 1024
2.003686 IP 10.1.1.2.9 > 10.1.1.1.49153: UDP, length 1024
```

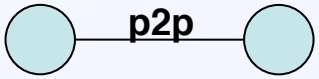
Chapter 6: Building topologies

Source material:

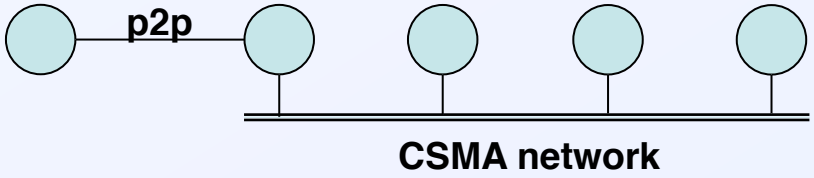
- **Online tutorial:** http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html#building-topologies
- **G. Riley (2008):** http://www.wns2.org/docs/wns_tutorial-handout.pdf

The goal of this chapter

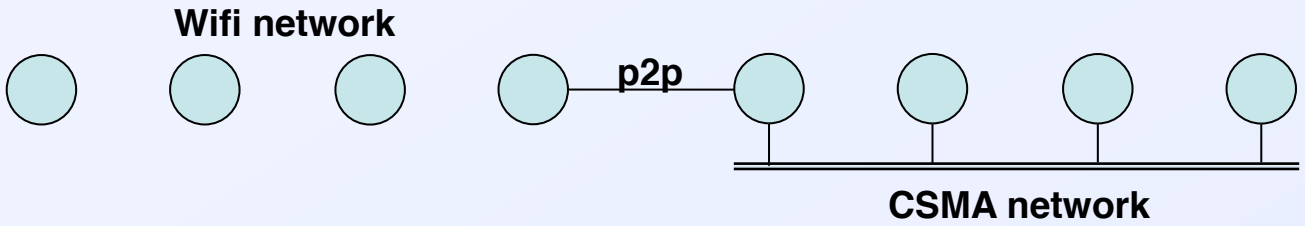
Expand from this:



To this:



And then to this:



Anatomy of the second.cc script (orange⇒ not in first.cc)

```
#include "ns-3/core-module.h"
#include "ns-3/network-module.h"
#include "ns-3/csma-module.h"
#include "ns-3/internet-module.h"
#include "ns-3/point-to-point-module.h"
#include "ns-3/applications-module.h"
#include "ns-3/ipv4-global-routing-helper.h"

using namespace ns-3;

NS_LOG_COMPONENT_DEFINE ("SecondScriptExample");

int main (int argc, char *argv[])
{
  bool verbose = true;
  uint32_t nCsma = 3;

  CommandLine cmd;
  cmd.AddValue ("nCsma", "Number of \"extra\" CSMA nodes/devices", nCsma);
  cmd.AddValue ("verbose", "Tell echo applications to log if true", verbose);

  cmd.Parse (argc,argv);

  if (verbose)
    {
      LogComponentEnable ("UdpEchoClientApplication", LOG_LEVEL_INFO);
      LogComponentEnable ("UdpEchoServerApplication", LOG_LEVEL_INFO);
    }

  nCsma = nCsma == 0 ? 1 : nCsma;

  NodeContainer p2pNodes;
  p2pNodes.Create (2);

  NodeContainer csmaNodes;
  csmaNodes.Add (p2pNodes.Get (1));
  csmaNodes.Create (nCsma);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

  NetDeviceContainer p2pDevices;
  p2pDevices = pointToPoint.Install (p2pNodes);

  CsmaHelper csma;
  csma.SetChannelAttribute ("DataRate", StringValue ("100Mbps"));
  csma.SetChannelAttribute ("Delay", TimeValue (NanoSeconds (6560)));

  NetDeviceContainer csmaDevices;
  csmaDevices = csma.Install (csmaNodes);

  InternetStackHelper stack;
  stack.Install (p2pNodes.Get (0));
  stack.Install (csmaNodes);

  Ipv4AddressHelper address;
  address.SetBase ("10.1.1.0", "255.255.255.0");
  Ipv4InterfaceContainer p2pInterfaces;
  p2pInterfaces = address.Assign (p2pDevices);

  address.SetBase ("10.1.2.0", "255.255.255.0");
  Ipv4InterfaceContainer csmaInterfaces;
  csmaInterfaces = address.Assign (csmaDevices);

  UdpEchoServerHelper echoServer (9);

  ApplicationContainer serverApps = echoServer.Install (csmaNodes.Get
(nCsma));
  serverApps.Start (Seconds (1.0));
  serverApps.Stop (Seconds (10.0));

  UdpEchoClientHelper echoClient (csmaInterfaces.GetAddress (nCsma), 9);
  echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
  echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.)));
  echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

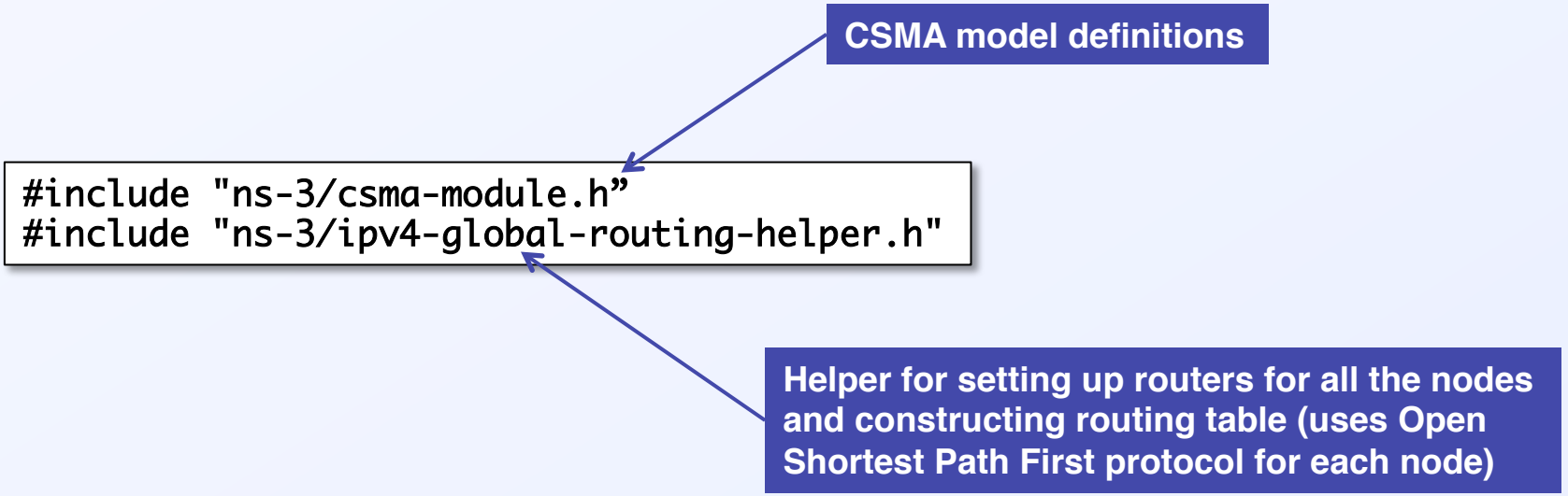
  ApplicationContainer clientApps = echoClient.Install (p2pNodes.Get (0));
  clientApps.Start (Seconds (2.0));
  clientApps.Stop (Seconds (10.0));

  Ipv4GlobalRoutingHelper::PopulateRoutingTables ();

  pointToPoint.EnablePcapAll ("second");
  csma.EnablePcap ("second", csmaDevices.Get (1), true);

  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```

What's new? A couple of additional include files



What's new? Command line parser

```
bool verbose = true;
uint32_t nCsma = 3;

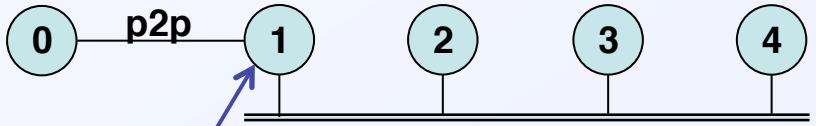
CommandLine cmd;
cmd.AddValue ("nCsma", "Number of \"extra\" CSMA nodes/devices", nCsma);
cmd.AddValue ("verbose", "Tell echo applications to log if true", verbose);

cmd.Parse (argc,argv);

nCsma = nCsma == 0 ? 1 : nCsma;
```

- Default value nCsma = 3
- CommandLine class can be used to parse command-line arguments
- User can register new arguments with AddValue(name,help,value)
  - name = name of user-supplied argument
  - help = some help text
  - value = reference to the variable where the value parsed will be stored
- The Parse method does exactly what it sounds like it does

What's new? Two devices on a single node



Point-to-point and CSMA devices

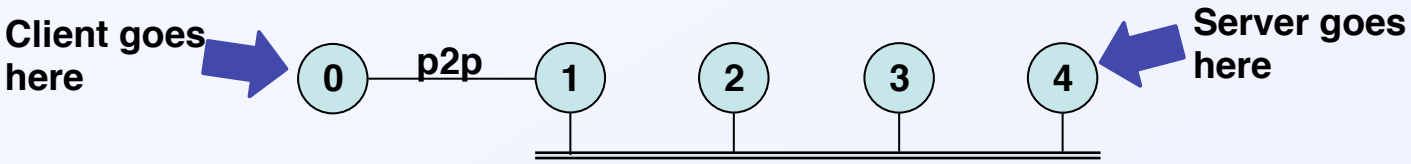
```
csmaNodes.Add (p2pNodes.Get (1));
```

Node 1 will get both types of devices

```
stack.Install (p2pNodes.Get (0));
stack.Install (csmaNodes);
```

No need to install a stack twice on node 1

What's new? Where do we put the client and server?




```
NodeContainer csmaNodes;
csmaNodes.Add (p2pNodes.Get (1));
csmaNodes.Create (nCsma);
```

Adds our dual-purpose node

Creates nCsma=3 additional nodes

- `nCsma` is the index of the last node in `csmaNodes`
- ⇒ The following lines refer to the server all the way to the right

```
ApplicationContainer serverApps = echoServer.Install (csmaNodes.Get (nCsma));
```

```
UdpEchoClientHelper echoClient (csmaInterfaces.GetAddress (nCsma), 9);
```

- The following line installs the client all the way to the left

```
ApplicationContainer clientApps = echoClient.Install (p2pNodes.Get (0));
```

What's new? Not much else…

```
Ipv4GlobalRoutingHelper::PopulateRoutingTables ();
```

Constructs the routing tables

- The rest looks almost identical to the p2p setup

Set channel attributes and install CSMA devices

```
CsmaHelper csma;
csma.SetChannelAttribute ("DataRate", StringValue ("100Mbps"));
csma.SetChannelAttribute ("Delay", TimeValue (NanoSeconds (6560)));

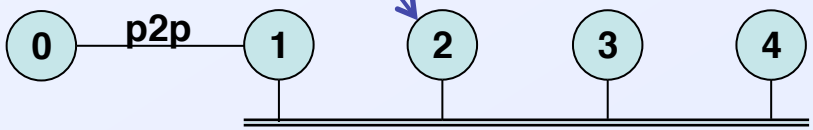
NetDeviceContainer csmaDevices;
csmaDevices = csma.Install (csmaNodes);
```

```
address.SetBase ("10.1.2.0", "255.255.255.0");
Ipv4InterfaceContainer csmaInterfaces;
csmaInterfaces = address.Assign (csmaDevices);
```

Assign IP addresses to CSMA devices

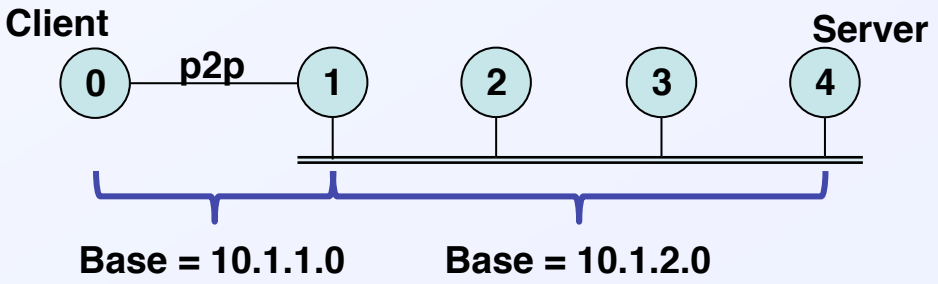
```
csma.EnablePcap ("second", csmaDevices.Get (1), true);
```

File prefix | Device id | Promiscuous mode

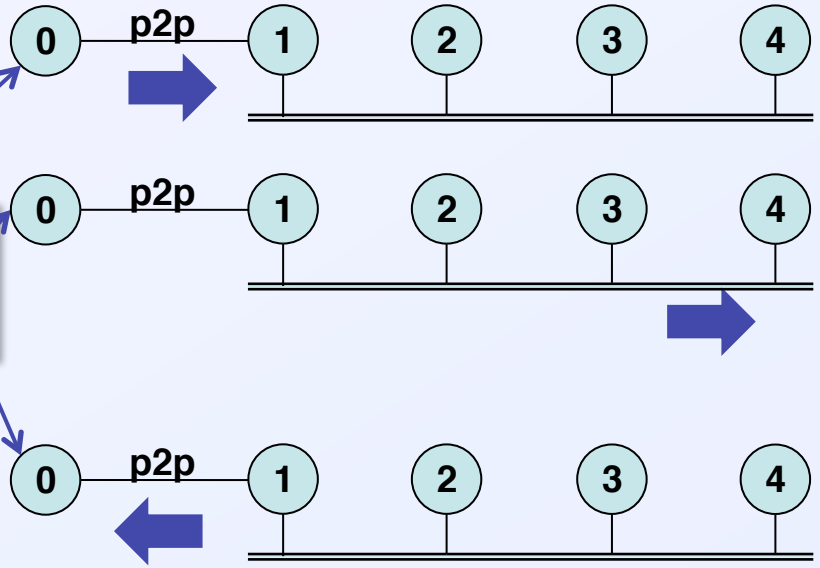


Running mysecond: logging output to console

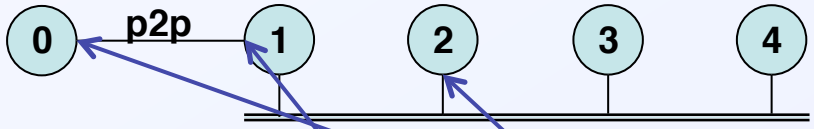
```
$ setenv NS_LOG=“”
$ ./waf –run scratch/mysecond
```




```
Sent 1024 bytes to 10.1.2.4
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.2.4
```



Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

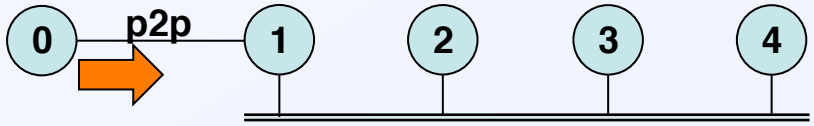
```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

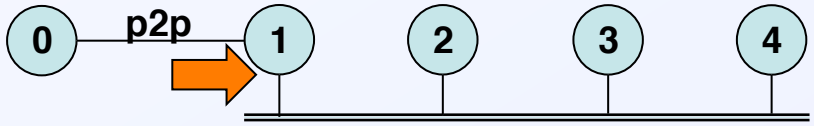
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Packet leaves client, headed for server

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

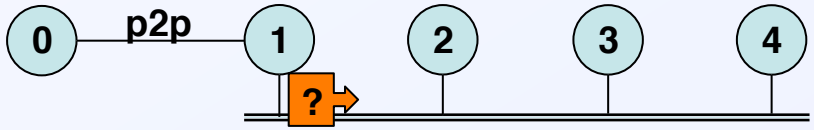
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Packet reaches node 1 on p2p network

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

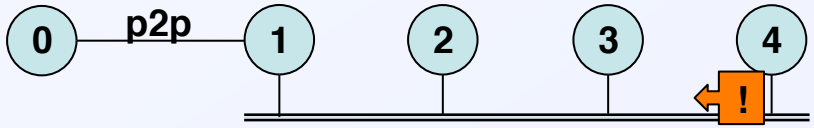
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node 1 broadcasts request on CSMA network

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

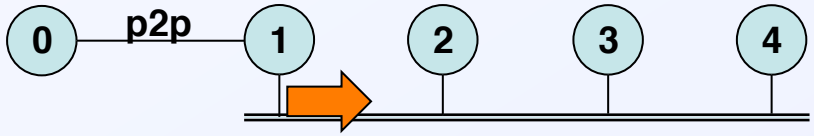
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node 4 replies with MAC address

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

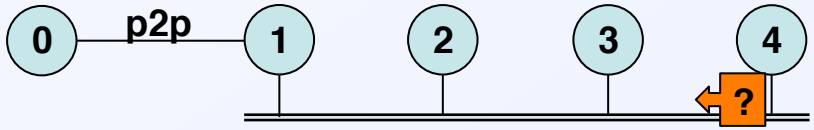
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Packet continues on its way to server

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

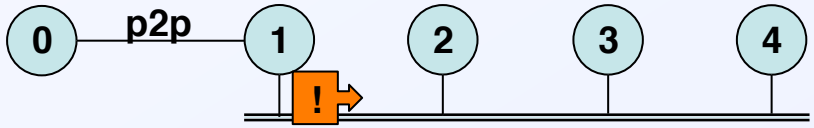
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Server broadcasts request for address of 1st CSMA node

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
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reading from file second-1-0.pcap, link-type PPP (PPP)
2.003686 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

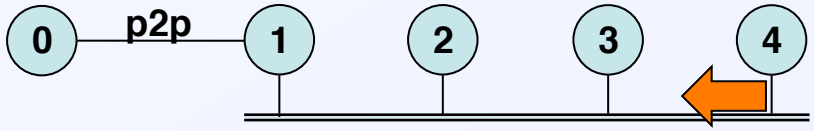
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

1st CSMA node replies with MAC address

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
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reading from file second-1-0.pcap, link-type PPP (PPP)
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2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

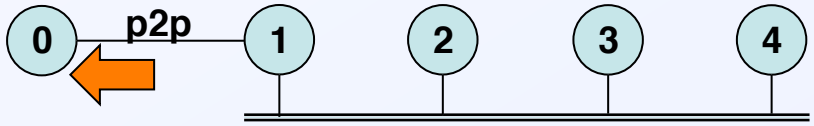
Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Server echoes the packet back

Running mysecond.cc: PCAP files




```
$ /usr/sbin/tcpdump -nn -tt -r second-0-0.pcap
reading from file second-0-0.pcap, link-type PPP (PPP)
2.000000 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.007607 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

Node = 0
Device = 0 (p2p)

```
$ /usr/sbin/tcpdump -nn -tt -r second-1-0.pcap
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```

Node = 1
Device = 0 (p2p)

Node = 2
Device = 0 (CSMA)

```
$ /usr/sbin/tcpdump -nn -tt -r second-2-0.pcap
reading from file second-2-0.pcap, link-type EN10MB (Ethernet)
2.003698 ARP, Request who-has 10.1.2.4 (ff:ff:ff:ff:ff:ff) tell 10.1.2.1, length 50
2.003710 ARP, Reply 10.1.2.4 is-at 00:00:00:00:00:06, length 50
2.003803 IP 10.1.1.1.49153 > 10.1.2.4.9: UDP, length 1024
2.003815 ARP, Request who-has 10.1.2.1 (ff:ff:ff:ff:ff:ff) tell 10.1.2.4, length 50
2.003828 ARP, Reply 10.1.2.1 is-at 00:00:00:00:00:03, length 50
2.003921 IP 10.1.2.4.9 > 10.1.1.1.49153: UDP, length 1024
```

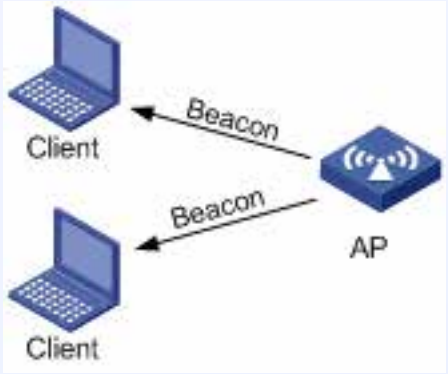
Echoed packet reaches the client

Models, attributes and reality

- Existing model implementations
  - Network stacks: arp, ipv4, icmpv4, udp, tcp, ipv6 (under review)
  - Devices: wifi, csma, point-to-point, bridge
  - Error models and queues
  - Applications: udp echo, on/off, sink
  - Mobility models: random walk, etc.
  - Routing: olsr, static global
- See files in `src/*/model` for details
- Easiest way to control model behavior is through attributes
  - Up to you to set realistic attributes

Wireless networks 101

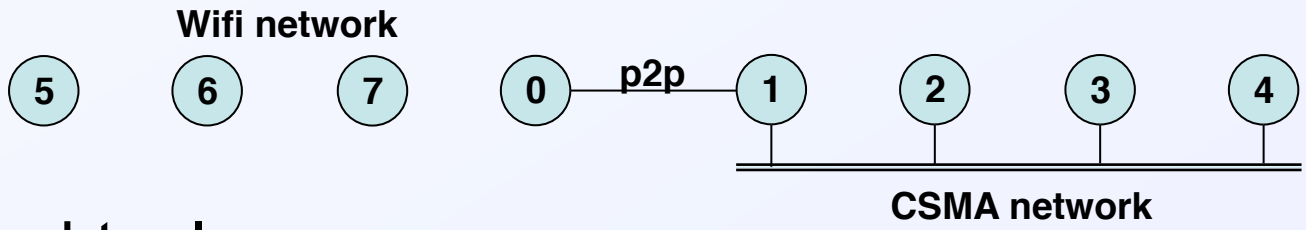
- Access point (AP) sends out beacons to advertise WLAN presence by revealing its Service Set ID (SSID = network name)
- WLAN client can
  - Broadcast probe request, wait for AP response (= active probing)
  - Wait for beacon from AP (= passive probing)
- Then (authentication followed by) association



Creating a wireless network with ns-3: `third.cc`

- Create 2 types of nodes
  - Stations
  - Access Points (AP)
- Create physical layer and channel, and associate
- Create MAC layer characteristics for node type
  - QoS or non-QoS
  - Assign Service Set Identifier (SSID)
  - And other MAC related attributes
- Install devices to nodes
- Set up mobility models
- Configure internet stack, application, routing models

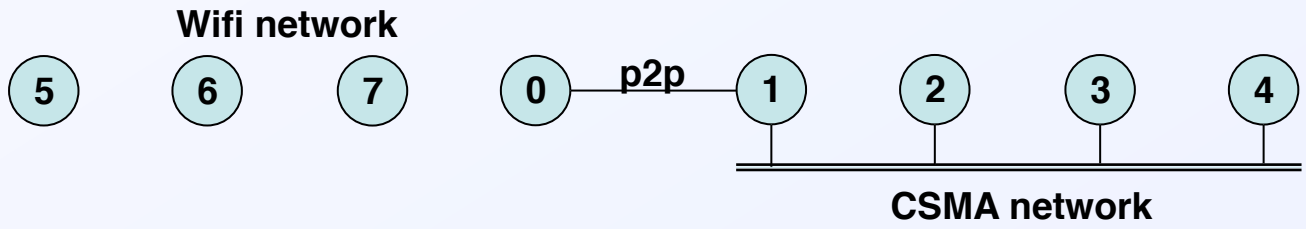
Creating a wireless network with ns-3: `third.cc`



- Network topology
  - Wireless nodes/links
    - 3 STA nodes
    - 1 AP node
    - 802.11 links, non-QoS mode, beaconing enabled
  - Wired nodes
    - 2 connected via p2p link
    - 4 nodes on a CSMA LAN
- Applications: UdpEchoClient/Server
  - Client on a STA node
  - Server on CSMA subnetwork

Let's focus on the wireless-specific parts of the code

Use helpers to create wireless channel/physical/MAC models



Create `nWifi = 3` station nodes

```
NodeContainer wifiStaNodes;
wifiStaNodes.Create (nWifi);
NodeContainer wifiApNode = p2pNodes.Get (0);

YansWifiChannelHelper channel = YansWifiChannelHelper::Default ();
YansWifiPhyHelper phy = YansWifiPhyHelper::Default ();
phy.SetChannel (channel.Create ());

WifiHelper wifi = WifiHelper::Default ();
wifi.SetRemoteStationManager ("ns-3::AarfWifiManager");

NqosWifiMacHelper mac = NqosWifiMacHelper::Default ();
```

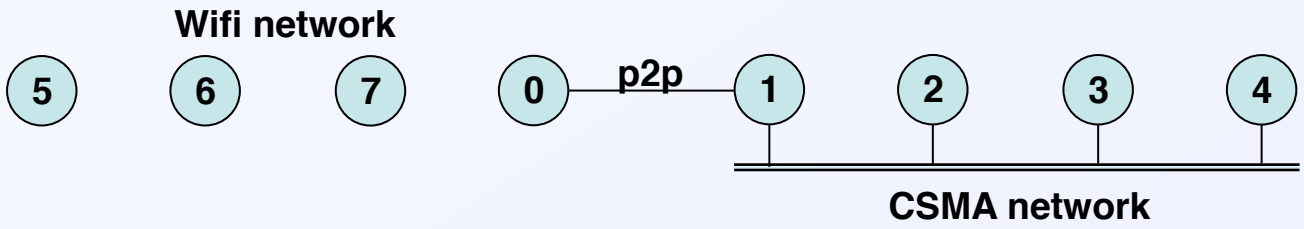
Create 1 AP node

Configure the physical and channel helpers

Connect all physical layer objects via the wireless channel

Configure the MAC layer
- Use non-QoS MACs
- Use AARF rate-control algorithm

Configure MAC types and install Wifi devices




```
NqosWifiMacHelper mac = NqosWifiMacHelper::Default ();
```

```
Ssid ssid = Ssid ("ns-3-ssid");
mac.SetType ("ns-3::StaWifiMac",
             "Ssid", SsidValue (ssid),
             "ActiveProbing", BooleanValue (false));

NetDeviceContainer staDevices;
staDevices = wifi.Install (phy, mac, wifiStaNodes);

mac.SetType ("ns-3::ApWifiMac",
             "Ssid", SsidValue (ssid)
             "BeaconGeneration",BooleanValue(true),
             "BeaconInterval",TimeValue(Seconds(2.5)));

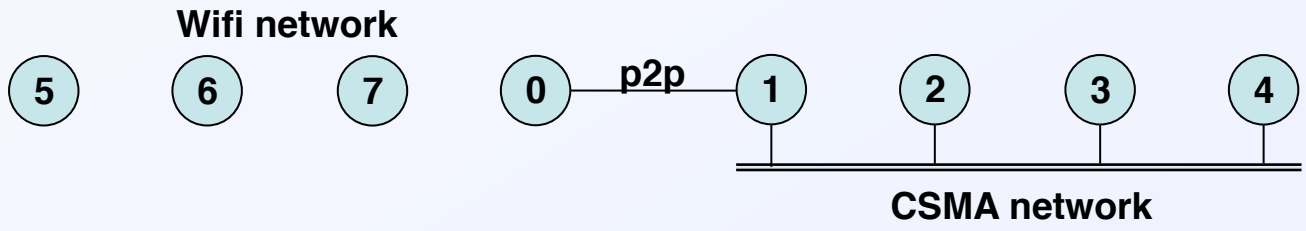
NetDeviceContainer apDevices;
apDevices = wifi.Install (phy, mac, wifiApNode);
```

Station nodes:
- 802.11 Service Set Identifier
- No QoS support
- Active probing disabled

Access point node:
- 802.11 Service Set Identifier
- No QoS support
- Beacon frames every 2.5 sec

These lines may be missing in your `third.cc`: add by hand

Associate mobility models with all wireless nodes

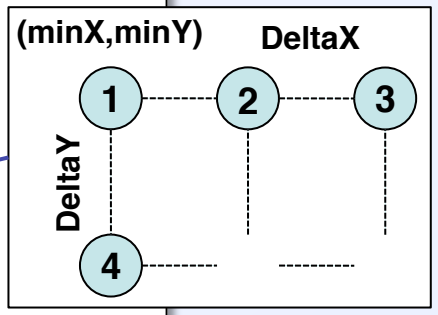



```
MobilityHelper mobility;

 mobility.SetPositionAllocator ("ns-3::GridPositionAllocator",
                                "MinX", DoubleValue (0.0),
                                "MinY", DoubleValue (0.0),
                                "DeltaX", DoubleValue (5.0),
                                "DeltaY", DoubleValue (10.0),
                                "GridWidth", UintegerValue (3),
                                "LayoutType", StringValue ("RowFirst"));

 mobility.SetMobilityModel ("ns-3::RandomWalk2dMobilityModel",
                            "Bounds", RectangleValue (Rectangle (-50, 50, -50, 50)));
 mobility.Install (wifiStaNodes);

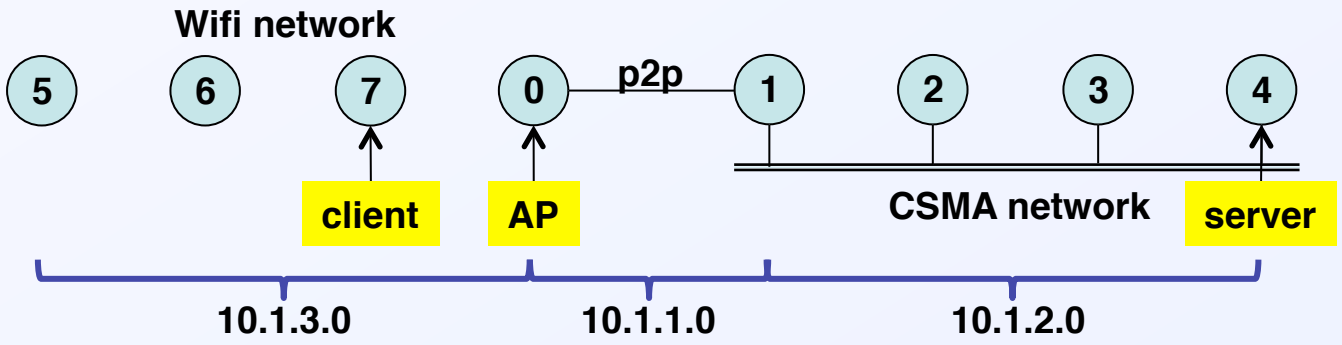
 mobility.SetMobilityModel ("ns-3::ConstantPositionMobilityModel");
 mobility.Install (wifiApNode);
```



Brownian-motion model with elastic scattering off boundaries

Fixed access point

Some final points before we run the simulation




```
Simulator::Stop (Seconds (10.0));
```

Needed to prevent AP from scheduling an endless sequence of beacon events

Trace on:
node 0, p2p device
node 1, p2p device

```
pointToPoint.EnablePcapAll ("third");
phy.EnablePcap ("third", apDevices.Get (0));
csma.EnablePcap ("third", csmaDevices.Get (0), true);
```

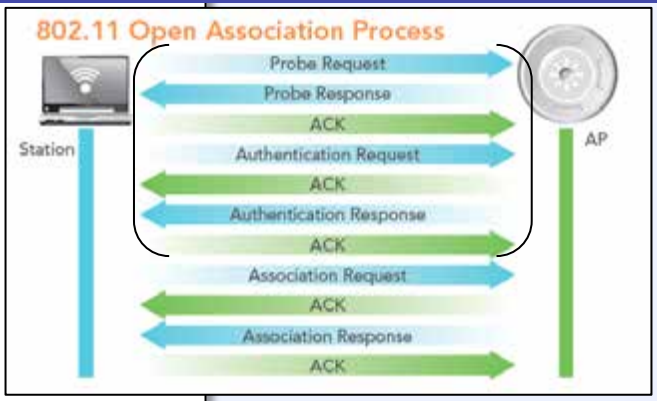
Trace on node 0, Wifi device

Promiscuous trace on node 1, CSMA device

Running `mythird.cc`: PCAP trace of the Wifi network

```
$ /usr/sbin/tcpdump -nn -tt -r third-0-1.pcap
reading from file third-0-1.pcap, link-type IEEE802_11 (802.11)
0.000025 Beacon () [6.0* 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit] IBSS
0.000263 Assoc Request () [6.0 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit]
0.000279 Acknowledgment RA:00:00:00:00:00:09
0.000552 Assoc Request () [6.0 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit]
0.000568 Acknowledgment RA:00:00:00:00:00:07
0.000664 Assoc Response AID(0) :: Succesful
0.001001 Assoc Response AID(0) :: Succesful
0.001145 Acknowledgment RA:00:00:00:00:00:0a
0.001233 Assoc Response AID(0) :: Succesful
0.001377 Acknowledgment RA:00:00:00:00:00:0a
0.001597 Assoc Request () [6.0 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit]
0.001613 Acknowledgment RA:00:00:00:00:00:08
0.001691 Assoc Response AID(0) :: Succesful
0.001835 Acknowledgment RA:00:00:00:00:00:0a
2.000112 ARP, Request who-has 10.1.3.4 (ff:ff:ff:ff:ff:ff) tell 10.1.3.3, length 32
2.000128 Acknowledgment RA:00:00:00:00:00:09
2.000206 ARP, Request who-has 10.1.3.4 (ff:ff:ff:ff:ff:ff) tell 10.1.3.3,
2.000478 ARP, Reply 10.1.3.4 is-at 00:00:00:00:00:0a, length 32
2.000650 Acknowledgment RA:00:00:00:00:00:0a
2.002160 IP 10.1.3.3.49153 > 10.1.2.4.9: UDP, length 1024
2.002176 Acknowledgment RA:00:00:00:00:00:09
2.009767 ARP, Request who-has 10.1.3.3 (ff:ff:ff:ff:ff:ff) tell 10.1.3.4,
2.010026 ARP, Reply 10.1.3.3 is-at 00:00:00:00:00:09, length 32
2.010042 Acknowledgment RA:00:00:00:00:00:09
2.010201 IP 10.1.2.4.9 > 10.1.3.3.49153: UDP, length 1024
2.011737 Acknowledgment RA:00:00:00:00:00:0a
2.500000 Beacon () [6.0* 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit] IBSS
5.000000 Beacon () [6.0* 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit] IBSS
7.500000 Beacon () [6.0* 9.0 12.0 18.0 24.0 36.0 48.0 54.0 Mbit] IBSS
```

Association requests establish link between AP and rest of Wifi network



Relevant IP addresses:
10.1.3.3 = client on wifi network
10.1.3.4 = AP on wifi network
10.1.2.4 = server on CSMA network

Beacon interval = 2.5 s
Stop at 10 s

A little foreshadowing: trace sources and trace sink

Add before main in `mythird.cc`:

```
void CourseChange(std::string context,Ptr<const MobilityModel> model)
{
  Vector position = model->GetPosition();
  NS_LOG_UNCOND(context << " x = " << position.x << ", y = " << position.y);
}
```

Trace sink: Consumes trace info

Add before `Simulator::Run` **in** `mythird.cc`

```
std::ostringstream oss;
oss << "/NodeList/" << wifiStaNodes.Get(nWifi-1)->GetId() <<
  "/$ns-3::MobilityModel/CourseChange";
```

Constructs a config path to the trace source (= event) of interest

```
Config::Connect(oss.str(),MakeCallback(&CourseChange));
```

Connects trace source to trace sink

A little foreshadowing: traced output

```
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 10, y = 0
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.68106, y = -0.947776
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 8.91651, y = -1.59234
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 8.42621, y = -2.46389
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.96741, y = -1.57536
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.38585, y = -2.38886
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.87379, y = -3.26174
Sent 1024 bytes to 10.1.2.4
Received 1024 bytes from 10.1.3.3
Received 1024 bytes from 10.1.2.4
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 8.85355, y = -3.06157
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.85467, y = -3.01432
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 8.21562, y = -2.08173
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.24156, y = -2.30803
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 6.34385, y = -2.74863
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.25552, y = -2.33769
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 6.3352, y = -1.94652
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.28767, y = -2.25114
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 7.97984, y = -2.97288
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 8.91579, y = -2.62074
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.6986
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.0889
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.9898
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 10.761
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 11.304
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 10.5904, y = -2.10878
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 10.9779, y = -3.03067
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.98188, y = -2.94141
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.93763, y =
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.26281, y =
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 9.38935, y =
/NodeList/7/$ns-3::MobilityModel/CourseChange x = 10.3487, y =
```

`/NodeList/7/$ns-3::MobilityModel/CourseChange` is a namespace path to the `CourseChange` event on node 7 (the Wifi client node)

We will talk a lot more about trace sources & sinks, namespace paths, etc. in the next section!

Side note: a cautionary tale

Suppose you type in:

```
oss << "/NodeList/" << wifiStaNodes.Get (nWifi - 1)->GetId () << “$ns-3::MobilityModel/CourseChange";
```

Instead of:

```
oss << "/NodeList/" << wifiStaNodes.Get (nWifi - 1)->GetId () << "/$ns-3::MobilityModel/CourseChange";
```

(can you spot the difference?)

With the first version: no error messages, but none of the “/NodeList/7/$ns-3::MobilityModel/CourseChange x = …, y = …” are printed out!

Side note: a cautionary tale

Suppose you type in:

```
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```
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Chapter 7: Tracing

Source material:

- Online tutorial: http://www.nsnam.org/docs/release/3.14/tutorial/singlehtml/index.html#tracing
- T. Predojev (2012): http://wikienergy.cttc.es/images/2/2d/ns-3-tutorial-complete.pdf
- M. Lacage (2009): http://www.nsnam.org/tutorials/ns-3-tutorial-tunis-apr09.pdf
- G. Riley (2008): http://www.wns2.org/docs/wns_tutorial-handout.pdf
- S. Kristiansen (2010): http://www.uio.no/studier/emner/matnat/ifi/INF5090/v11/undervisningsmateriale/INF5090-ns-3-Tutorial-2011-Oslo-slides.pdf

More advanced tracing with ns-3

- You can use ascii, pcap tracing or logging to get info from your sim
  - Need to write code to parse output
  - The info you want may not be obtainable by pre-defined mechanisms
- There is another way in ns-3
  - Add your own traces to events you care about
  - Produce output in a convenient form
  - Add hooks to the core that can be accessed by other users later

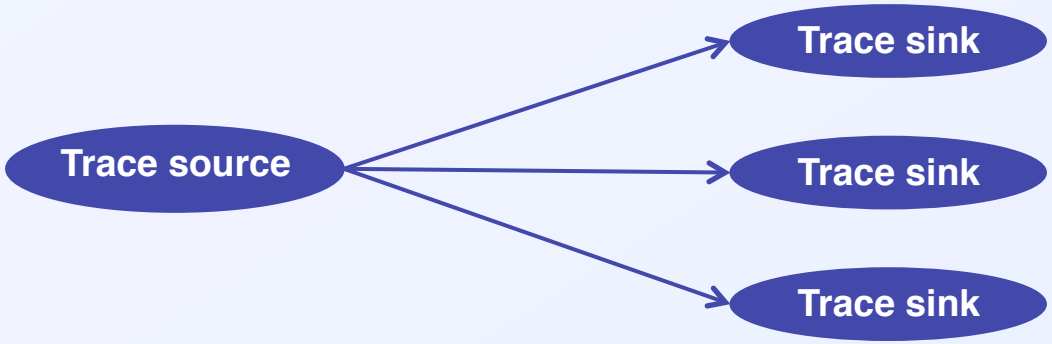
You could use print statements, but I wouldn't recommend it

- You may have to dig deep inside the ns-3 core to find the info you want
- More print statements ⇒ need way to enable/disable specific ones
  - Congratulations! You've just re-invented the ns-3 logging system!
- You could add logging statements to the core
  - Remember: ns-3 is open-source, evolving system
    - Core will bloat to include all possible log messages
    - Unwieldy gigantic log files ⇒ effectively useless
    - No guarantee specific log messages will survive releases

Logging ≠ Tracing

The basic idea: trace sources and sinks

- You need:
  1. Trace source: signals sim event and provides access to the data
  2. Trace sink: consumes the trace info, do something useful with it
  3. Mechanism to connect trace source to trace sink
- Note: there can be many sinks connected to the same trace source



A simple low-level example: callbacks

- This is the key to the way tracing works
- In C/C++ you can pass a pointer to a function: callback mechanism

A numeric function

A function to integrate numeric functions

Integrate myFunction

```
float
myFunction(float x)
{
  return x*x;
}
        ⋮
float
Integrate(float (*func)(float), float lo, float hi)
{
  …
}
        ⋮
Integrate(&myFunction, 0, 1);
```

- Trace source maintains a list of callback functions added by the sinks
- When an event of interest happens
  - Trace source passes data to the callback functions
  - Callback functions are executed

A simple low-level example: `fourth.cc`

```
#include "ns-3/object.h"
#include "ns-3/uinteger.h"
#include "ns-3/traced-value.h"
#include "ns-3/trace-source-accessor.h"

#include <iostream>

using namespace ns-3;

class MyObject : public Object
{
public:
  static TypeId GetTypeId (void)
  {
    static TypeId tid = TypeId ("MyObject")
      .SetParent (Object::GetTypeId ())
      .AddConstructor<MyObject> ()
      .AddTraceSource ("MyInteger",
                       "An integer value to trace.",
                       MakeTraceSourceAccessor (&MyObject::m_myInt));
    return tid;
  }

  MyObject () {}
  TracedValue<int32_t> m_myInt;
};

void IntTrace (int32_t oldValue, int32_t newValue)
{
  std::cout << "Traced " << oldValue << " to " << newValue << std::endl;
}

int main (int argc, char *argv[])
{
  Ptr<MyObject> myObject = CreateObject<MyObject> ();
  myObject->TraceConnectWithoutContext ("MyInteger", MakeCallback (&IntTrace));

  myObject->m_myInt = 1234;
}
```

Goal: trace changes made to a variable

- **i.e., notify user whenever**
  - **+, ++, =, etc.**

Trace source

Trace sink

Connection

A simple-low level example: the trace source

MyObject is derived from Object, inherits public members

```
class MyObject : public Object
{
public:
  static TypeId GetTypeId (void)
  {
    static TypeId tid = TypeId ("MyObject")
      .SetParent (Object::GetTypeId ())
      .AddConstructor<MyObject> ()
      .AddTraceSource ("MyInteger",
                       "An integer value to trace.",
                       MakeTraceSourceAccessor (&MyObject::m_myInt));
    return tid;
  }

  MyObject () {}
  TracedValue<int32_t> m_myInt;
};
```

Always need GetTypeId method for an object

- Provides run-time info on type
- Allows objects to located via path (more on this later)
- Provides objects with attributes
- Provides objects with trace sources

A simple-low level example: the trace source

```
class MyObject : public Object
{
public:
  static TypeId GetTypeId (void)
  {
    static TypeId tid = TypeId ("MyObject")
      .SetParent (Object::GetTypeId ())
      .AddConstructor<MyObject> ()
      .AddTraceSource ("MyInteger",
                       "An integer value to trace.",
                       MakeTraceSourceAccessor (&MyObject::m_myInt));
    return tid;
  }

  MyObject () {}
  TracedValue<int32_t> m_myInt;
};
```

TypeId class records meta-information about MyObject

Provides unique identifier

Record TypeId of base class

Default constructor is accessible

Provides hook to connect to trace source:
- Name of source
- Help string
- Accessor = pointer to connect

Provides infrastructure to
- Overload operators
- Drive callback process

A simple low-level example: the trace sink

```
void IntTrace (int32_t oldValue, int32_t newValue)
{
  std::cout << "Traced " << oldValue << " to " << newValue << std::endl;
}
```

A simple void function

- **Takes in the old and new values of the traced variable**
  - **Will be supplied by the trace source**
- **Prints them to the screen**

A low-level example: the main function

ns-3 smart pointers provide garbage collection via reference counting
Track number of pointers to an object
Helps avoid memory leaks when you forget to delete an object

Wrapper for C++ “new”

```
int main (int argc, char *argv[])
{
  Ptr<MyObject> myObject = CreateObject<MyObject> ();
  myObject->TraceConnectWithoutContext ("MyInteger", MakeCallback (&IntTrace));

  myObject->m_myInt = 1234;
}
```

If all goes as planned:
should trigger callback

Connecting source to sink
- “MyInteger” = name of source
- Callback made from our sink function
- We’ll talk about “Context” next…

A low-level example: running fourth.cc

```
$ cp examples/tutorial/fourth.cc scratch/myfourth.cc
$ ./waf --run scratch/myfourth
```

```
Traced 0 to 1234
```

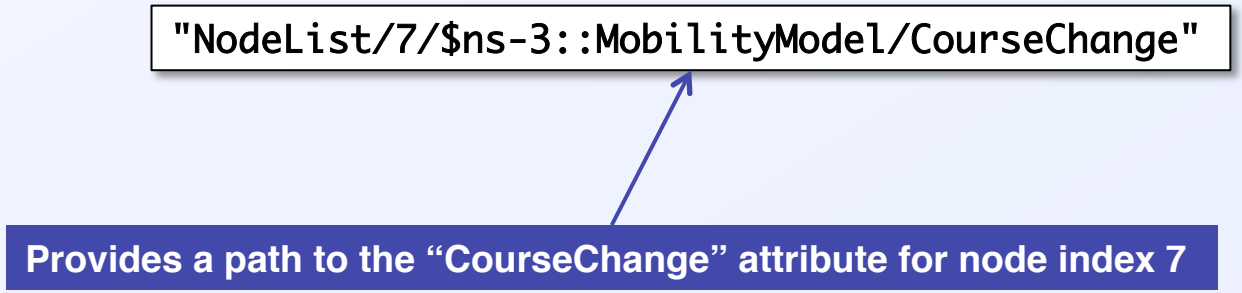
Assignment in: myObject->m_myInt = 1234; triggers callback

Seems almost anticlimactic, but we've illustrated the main steps in tracing

- **Define trace source**
- **Define trace sink**
- **Connect trace source to trace sink**

Using Config to connect to trace sources

- `TraceConnectWithoutContext` is not typical way to connect source to sink
- Normally done via the Config subsystem in ns-3, by using a config path
  - A string that looks like a file path
  - Represents chain of objects leading to the desired event (or attribute)
- We encountered this in `third.cc`



Let’s dissect this config path

Dissecting the Config path in `third.cc`

```
"NodeList/7/$ns-3::MobilityModel/CourseChange"
```

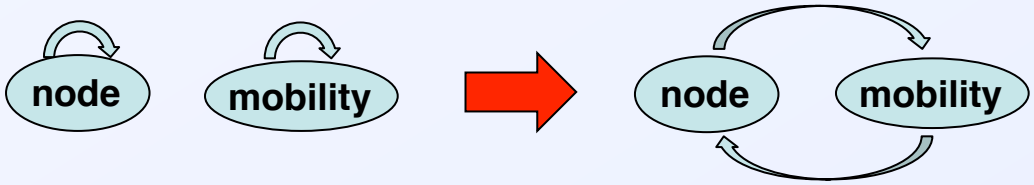
- "`NodeList`" = predefined namespace in Config, lists all the nodes in the sim
- "`NodeList/7`" = node 7 (i.e., the eigth node)
- "$" = what follows designates an aggregated object

Let's take a short detour to discuss aggregated objects in ns-3

Object aggregation in ns-3

- Makes it possible for objects to access each other, and for users to easily access objects in an aggregation
- Avoids need to modify a base class to provide pointers to all possible connected objects
  - Class definitions would bloat uncontrollably
  - Solution: separate functionality belongs to separate classes

```
Node->AggregateObject(mobility);
```



Retrieving an aggregated object:

```
Ptr<MobilityModel> mob = node->GetObject<MobilityModel> ();
```

Dissecting the Config path in third.cc

```
"NodeList/7/$ns-3::MobilityModel/CourseChange"
```

- "NodeList" = predefined namespace in Config, lists all the nodes in the sim
- "NodeList/7" = node 7 (i.e., the eigth node)
- "$" = what follows designates an aggregated object
- "/NodeList/7/$ns-3::MobilityModel" = get the mobility model object aggregated to node 7 in the sim
- "CourseChange" = attribute of MobilityModel we are interested in
- Config will follow the chain of pointers to the attribute you specified

```
Config::Connect("NodeList/7/$ns-3::MobilityModel/CourseChange",MakeCallback(&CourseChange))
```

- Ties the trace source to the trace sink callback function
- Passes the context (= config path) to the callback function

How to Find and Connect Trace Sources, and Discover Callback Signatures

- What trace sources are available (besides `CourseChange`)?
- How do I figure out the config path I need to connect to this source?
- What are the return type and arguments of my callback function?

```
void CourseChange(std::string context,Ptr<const MobilityModel> model)
```

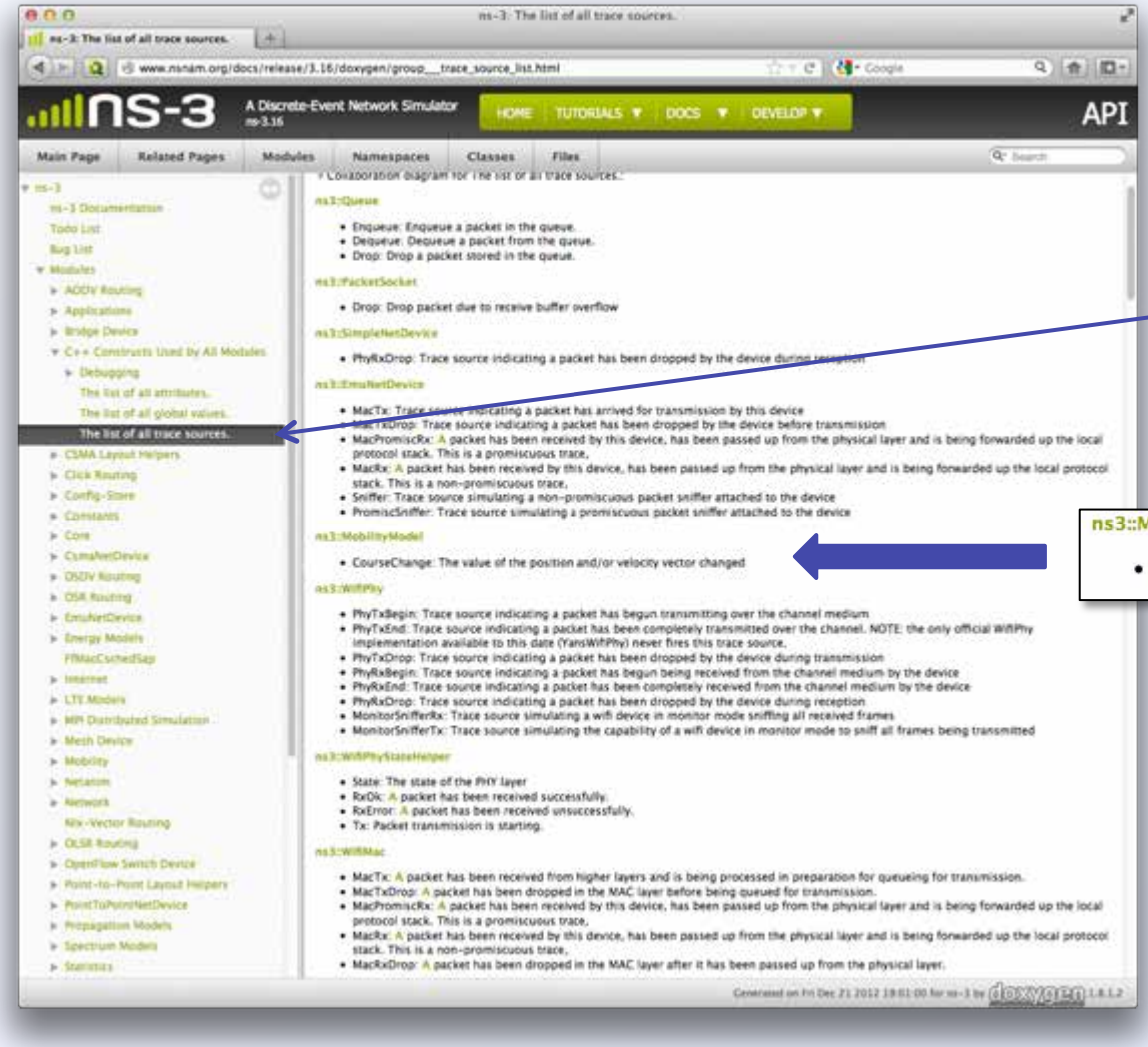
```
void IntTrace (int32_t oldValue, int32_t newValue)
```

Doxygen and a little detective work will go a long way here

What trace sources are available?

- Doxygen has the answer!
  - Trace sources: http://www.nsnam.org/docs/release/3.16/doxygen/group___trace_source_list.html
  - Attributes: http://www.nsnam.org/docs/release/3.16/doxygen/group___attribute_list.html
  - Global values: http://www.nsnam.org/docs/release/3.16/doxygen/group___global_value_list.html

What trace sources are available?



Doxygen's "The list of all trace sources"

ns3::MobilityModel

- CourseChange: The value of the position and/or velocity vector changed

What string do I use to connect?

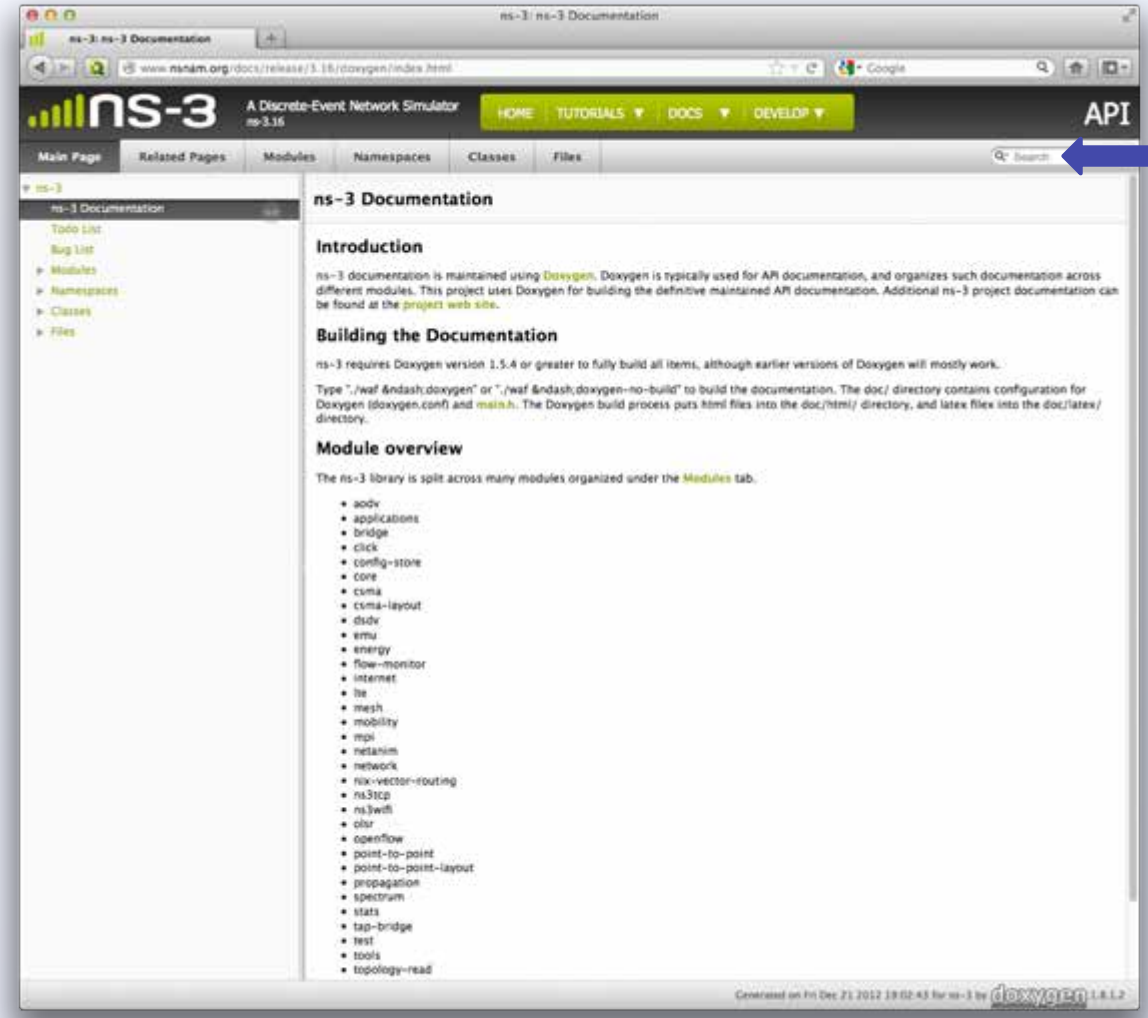
- **Method 1**: look for config path in someone else's code
  - `$ find -name "*.cc" | xargs grep CourseChange | grep Connect`

```
          ⋮
./src/mobility/examples/main-random-walk.cc:  Config::Connect ("/NodeList/*/
$ns-3::MobilityModel/CourseChange",
          ⋮
```

  - Config path = "/NodeList/*/$ns-3::MobilityModel/CourseChange"
    - You can use regular expressions in the path, so "*" ⇒ any node
    - "/NodeList/[3-5]|8|[0-1]" would match node indices 0,1,3,4,5,8

What string do I use to connect?

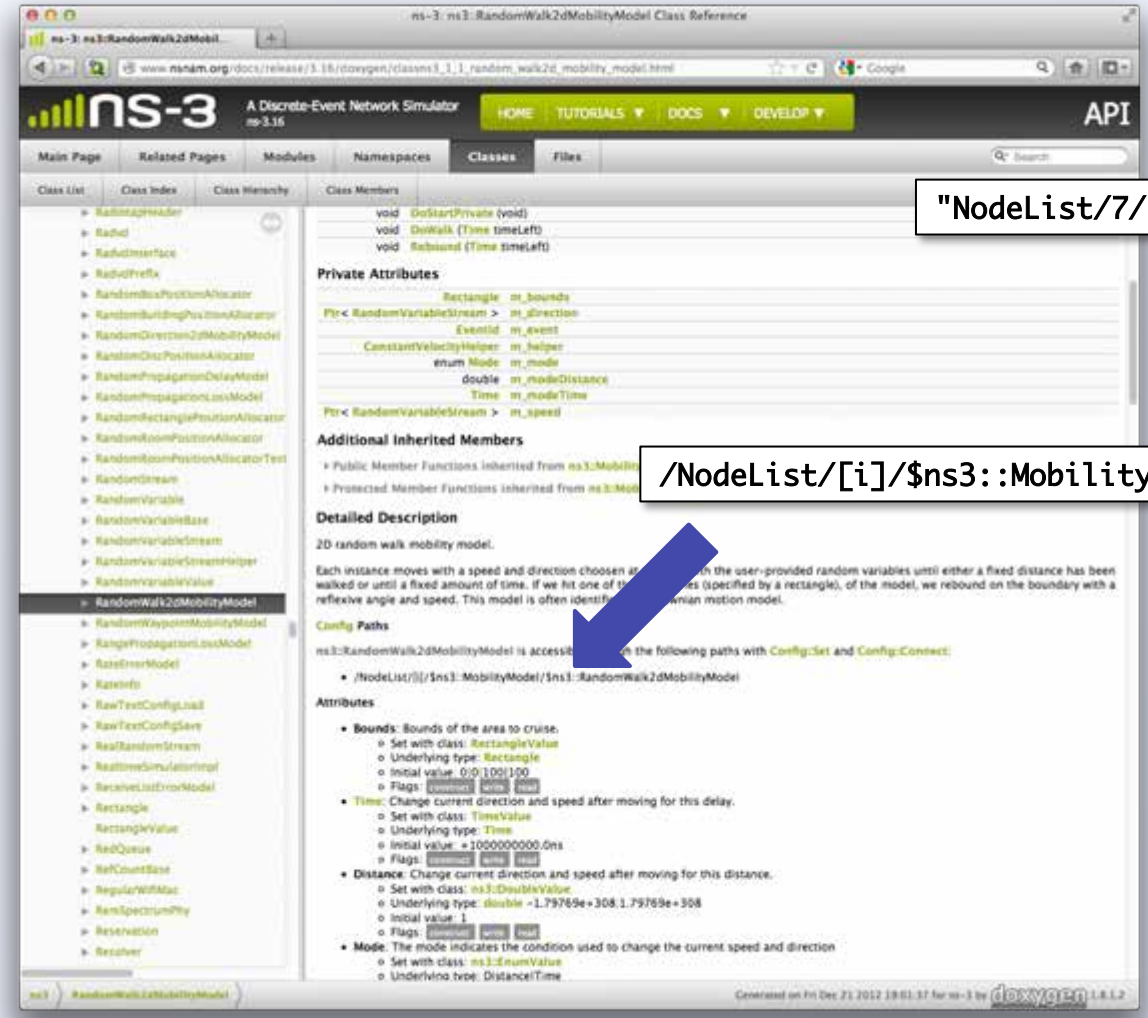
- **Method 2**: Doxygen



RandomWalk2dMobilityModel

What string do I use to connect?

- **Method 2: Doxygen**



Remember: before, we used:

`"NodeList/7/$ns-3::MobilityModel/CourseChange"`

We're almost there! We found:

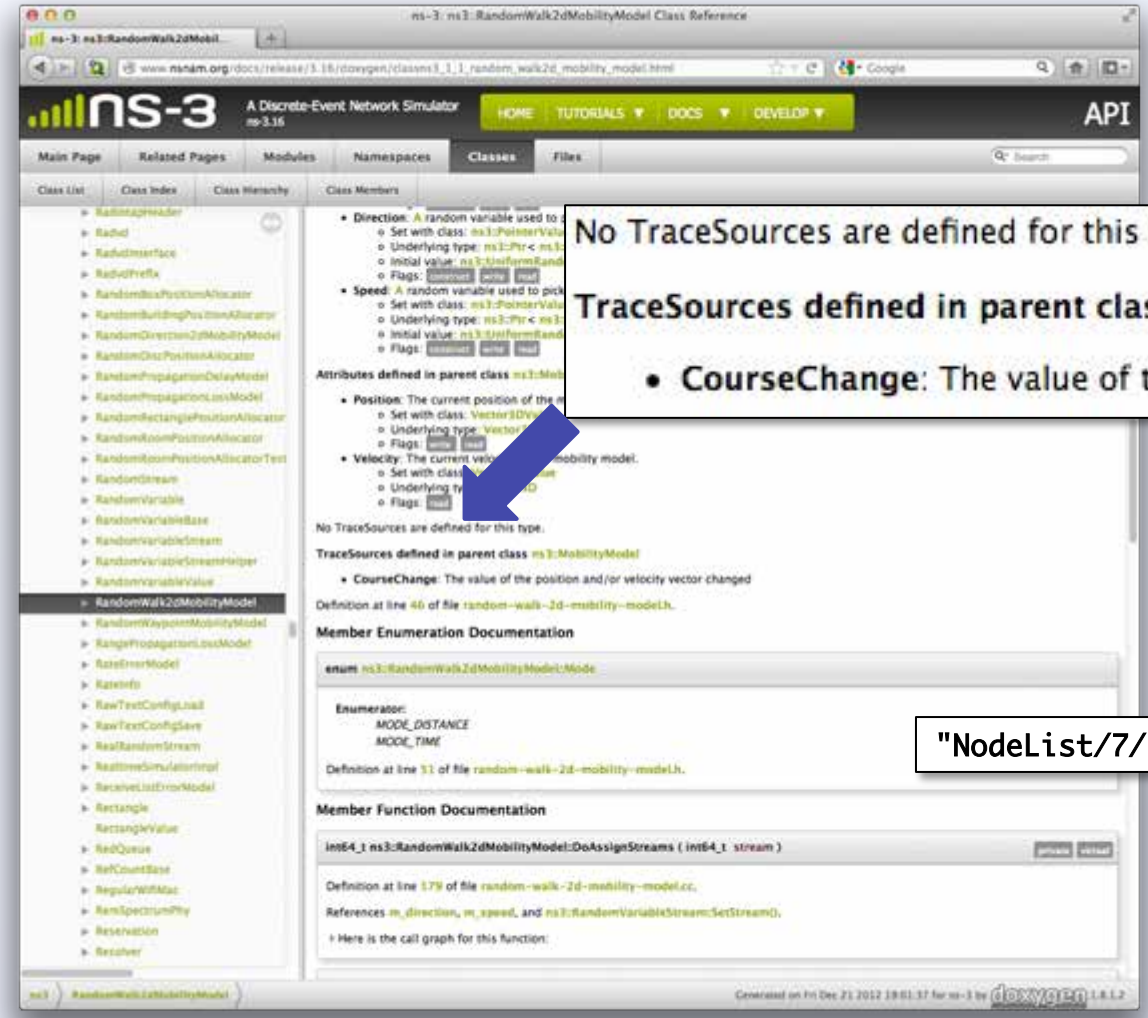
`/NodeList/[i]/$ns3::MobilityModel/$ns3::RandomWalk2dMobilityModel`

But what's this bit?

Scroll further down

What string do I use to connect?

- **method 2: Doxygen**



This tells you to access the "CourseChange" attribute from the parent class, so:

```
"NodeList/7/$ns-3::MobilityModel/CourseChange"
```

What are the return value and arguments for the callback function?

- The easy way: copy someone else's answer
  - `$ find -name "*.cc" | xargs grep CourseChange | grep Connect`

```
./src/mobility/examples/main-random-walk.cc:  Config::Connect ("/
NodeList/*/$ns-3::MobilityModel/CourseChange",
```

  - Inside "`./src/mobility/examples/main-random-walk.cc`":

```
Config::Connect ("/NodeList/*/$ns-3::MobilityModel/CourseChange",
                 MakeCallback (&CourseChange));
```

  - And we then find the declaration of the "`CourseChange`" function:

```
static void CourseChange (std::string foo, Ptr<const MobilityModel> mobility)
```

But what if you can't find what you need in someone else's code?

What return value and arguments for the callback function?

- The somewhat easy way
  - The return value is always "`void`"
  - To get the list of formal arguments, look in the "`.h`" file for the model
    - Find the "`TracedCallback`" declaration
    - For example, in "`src/mobility/model/mobility-model.h`"

```
TracedCallback<Ptr<const MobilityModel> > m_courseChangeTrace;
```

This is the argument we need!

    - So for callback using `Config::ConnectWithoutContext`

```
void CourseChange(Ptr<const MobilityModel> model)
```

    - And for callback using `Config::Connect`

```
void CourseChange(std::string path,Ptr<const MobilityModel> model)
```

Context (= config path) gets passed here

What about TracedValue?

- Remember we used the callback function

```
void IntTrace(int32_t oldValue, int32_t newValue)
```

- How did we guess the right formal arguments to use?
- Find "TracedCallback" declaration in "src/core/model/traced-value.h"

```
template <typename T>
class TracedValue
{
public:
  ...
private:
  T m_v;
  TracedCallback<T,T> m_cb;
};
```

Template class ⇒ you get to choose its type

- In fourth.cc, inside the MyObject class, we declared

```
TracedValue<int32_t> m_myInt;
```

⇒ T = int32_t

⇒ Two arguments in the callback, both of type T (i.e., int32_t)

A real example

From W. Richard Stevens, "TCP/IP Illustrated, Vol. I: The Protocols", Addison-Wesley (1994)

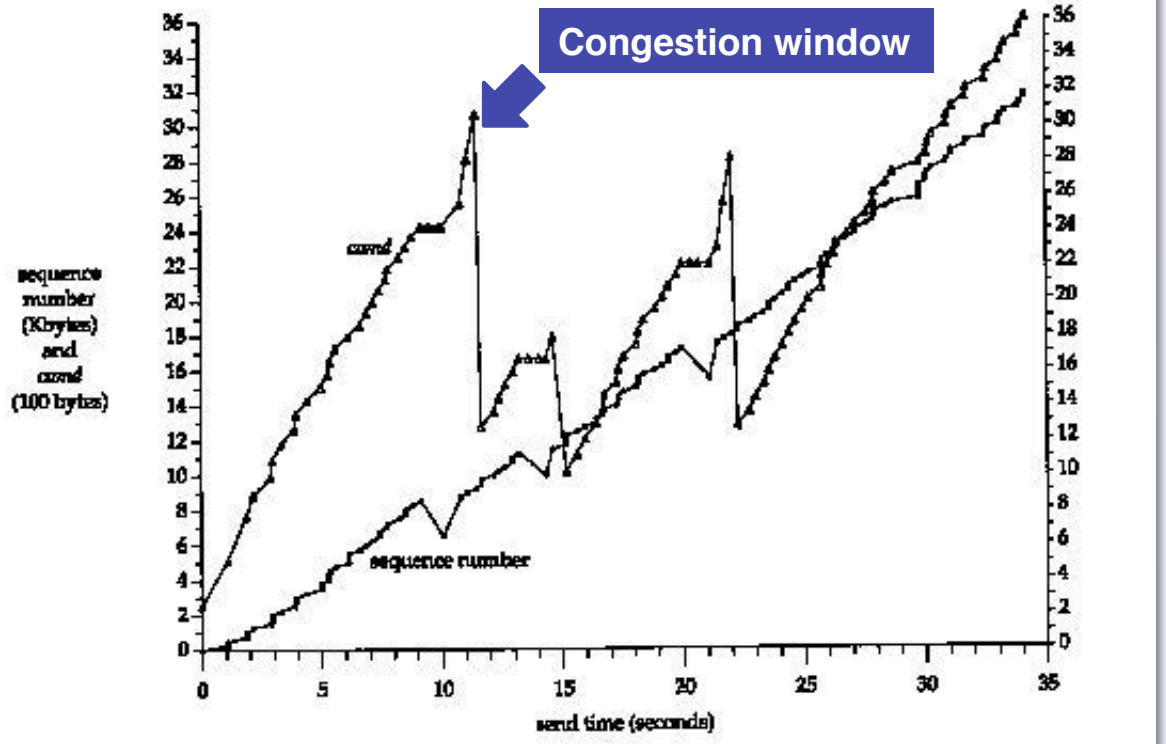


Figure 21.10 Value of *cwnd* and send sequence number while data is being transmitted.

Goal: simulate a TCP congestion window and look at the effect of dropped packets

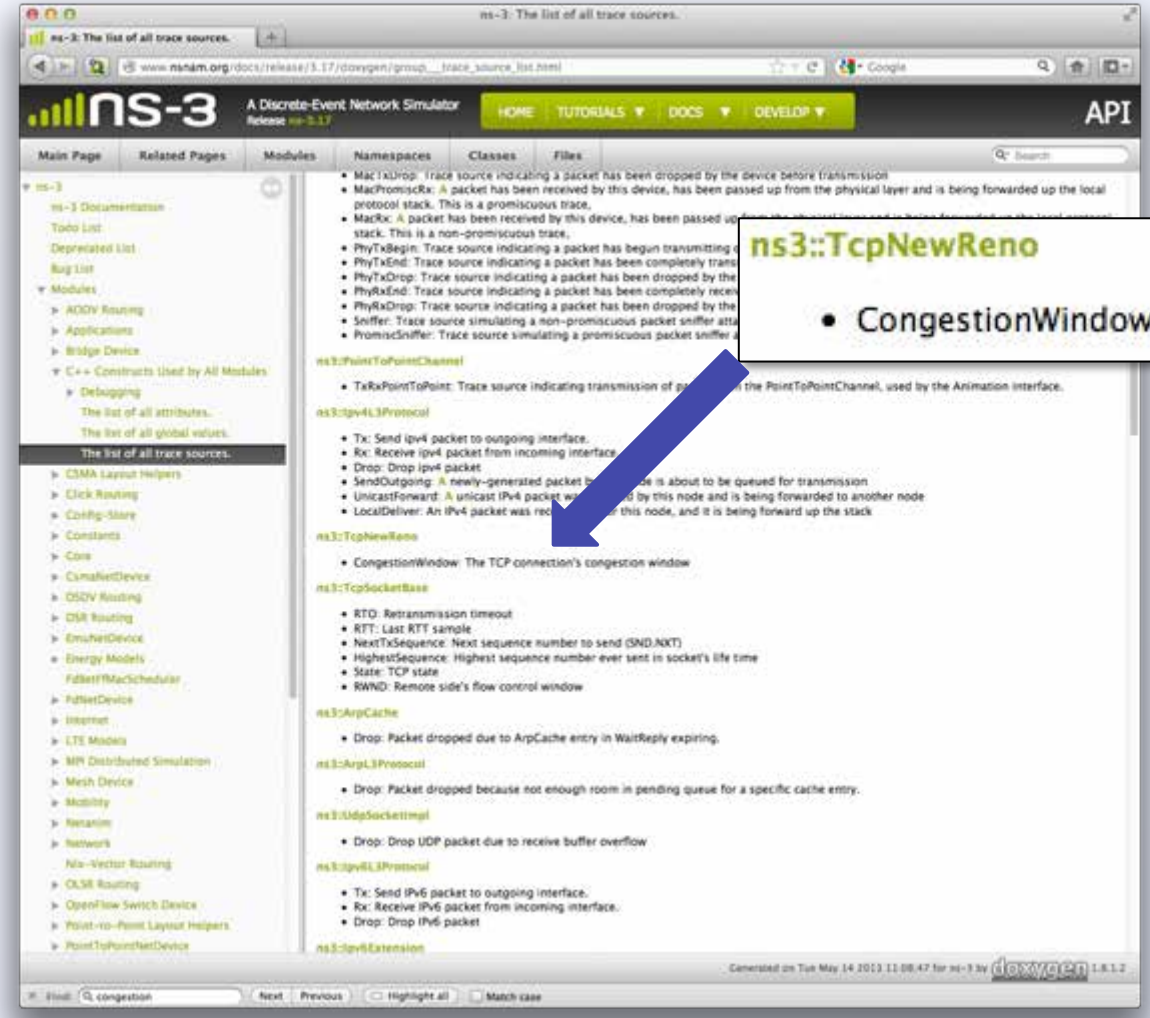
Congestion windows 101 (from Wikipedia)

- Congestion collapse occurs at choke points in the network
  - Wherever total incoming traffic to a node > outgoing bandwidth
  - e.g., connection points between LAN and WAN
- TCP uses network congestion avoidance algorithm
- Congestion window is part of TCP strategy to avoid congestion collapse
  - Limits total number of unacknowledged packets that may be in transit
  - The size of the window is adjusted dynamically by the sender
    - Based on how much congestion between sender and receiver
    - If all segments are received and the acks reach the sender on time
      - Add a constant to the window (typically 1 MSS = Max Segment Size)
    - Otherwise
      - Scale back by a set factor (typically 1/2)

Explains "sawtooth" shape of congestion window over time

Are there trace sources available?

- From Doxygen's "The list of all trace sources"



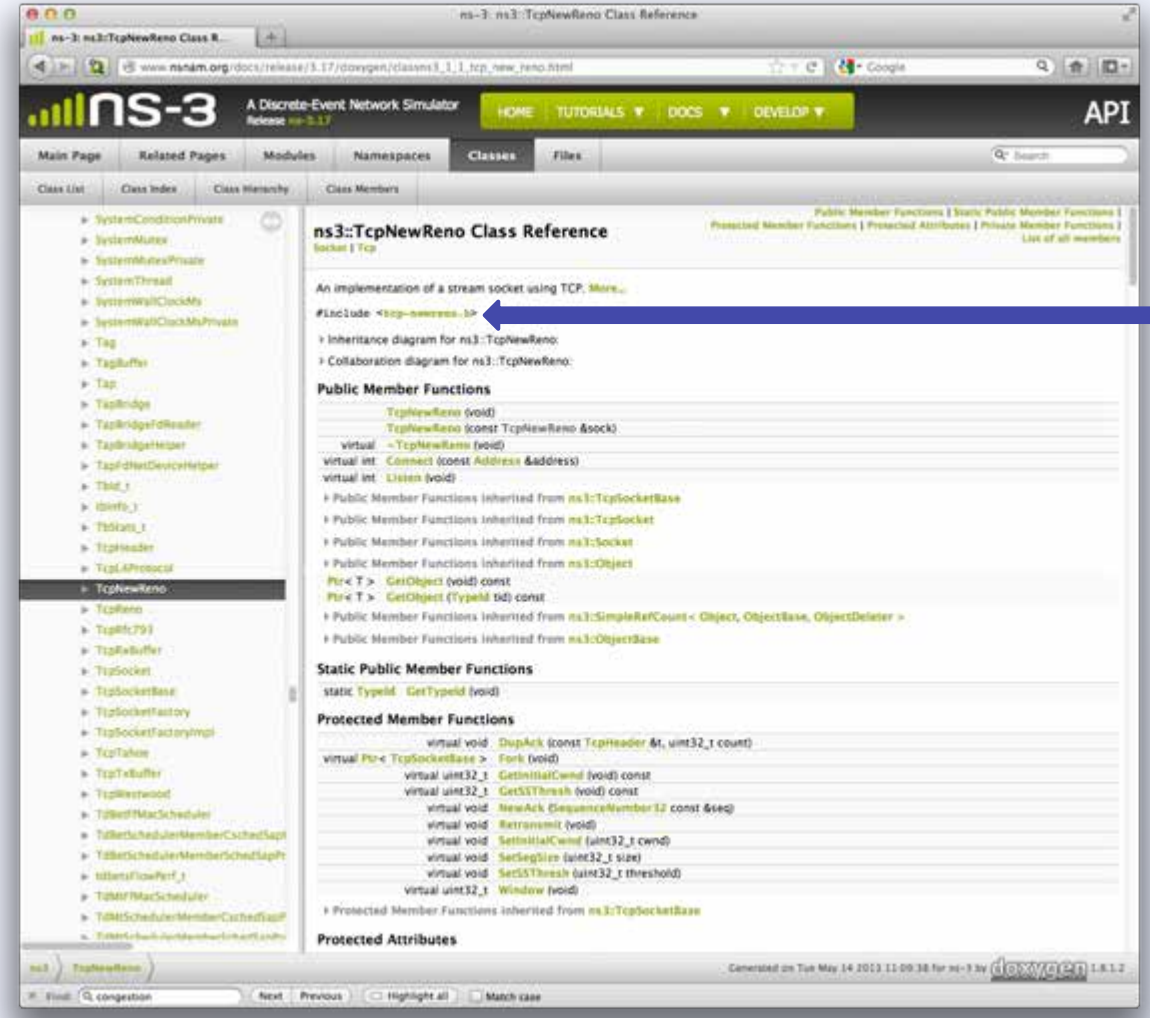
Look for "congestion":

We have our trace source: `CongestionWindow`

Click on "`ns-3::TcpNewReno`" to access class info

Are there trace sources available?

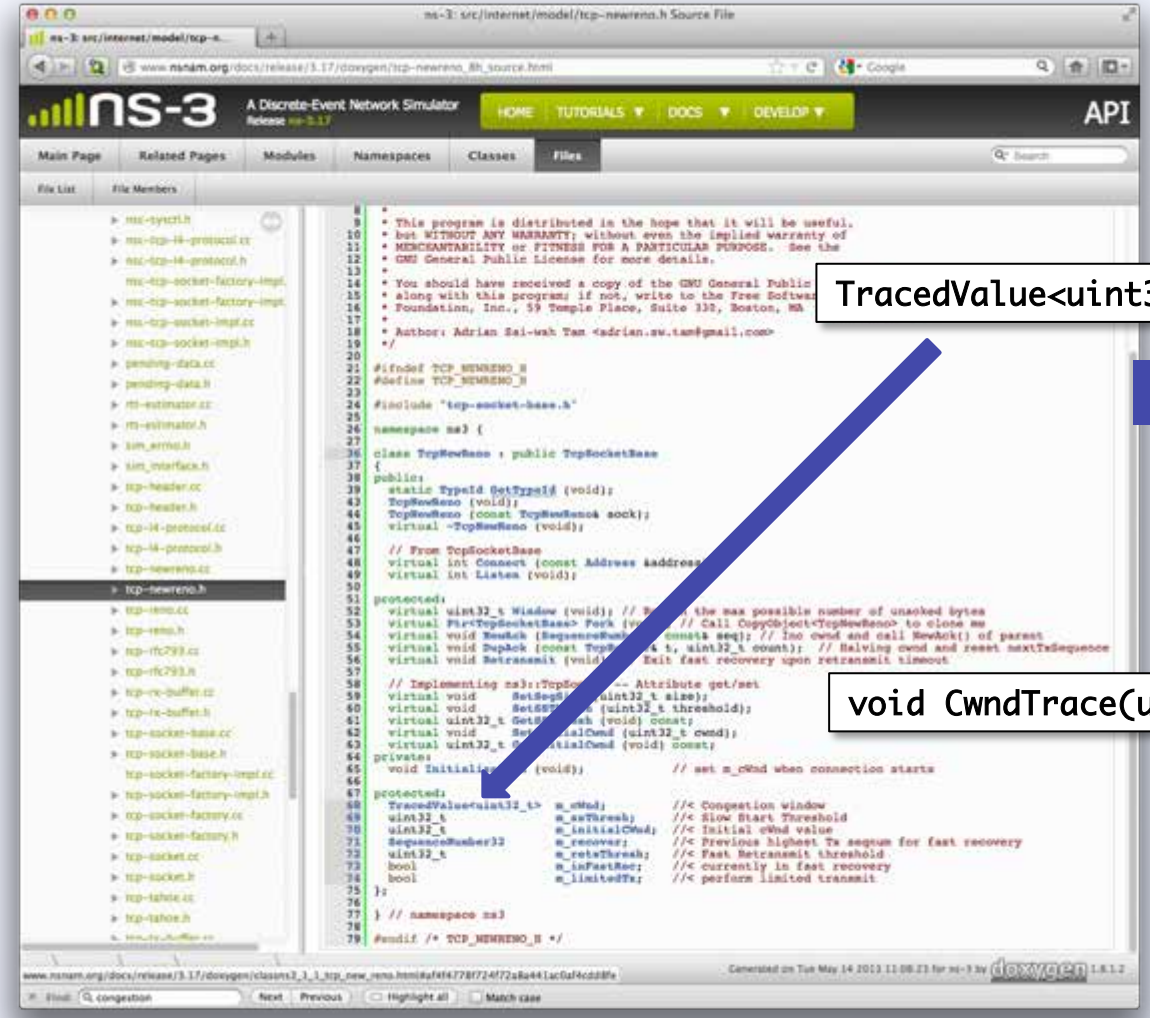
- From Doxygen's "The list of all trace sources"



Click on link to header file "tcp-newreno.h"
Look for keyword "congestion"

Are there trace sources available?

- From Doxygen's "The list of all trace sources"



How do we get started writing our script?

- The time-honored way: steal from someone else's code
  - `$ find . -name "*.cc" | xargs grep CongestionWindow`
  - Look, e.g., in "`./src/test/ns-3tcp/ns-3tcp-cwnd-test-suite.cc`"
  - The connection between trace and source is done by

```
ns-3TcpSocket->TraceConnectWithoutContext ("CongestionWindow",
MakeCallback (&ns-3TcpCwndTestCase1::CwndChange, this));
```

This is the callback function

```
void CwndChange (uint32_t oldCwnd, uint32_t newCwnd)
```

  - We can also copy code from the function

```
void ns-3TcpCwndTestCase1::DoRun (void)
```

This is how `fifth.cc` was put together

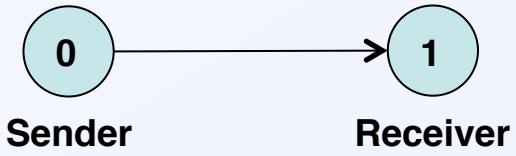
Avoiding a common mistake in ns-3

- ns-3 scripts execute in three separate stages
  - Configuration time
  - Simulation time (i.e., Simulator::Run)
  - Teardown time
- TCP uses sockets to connect nodes
  - Sockets are created dynamically during simulation time
    - Want to hook the `CongestionWindow` on the socket of the sender
  - Connection to trace sources is established during configuration time
  - Can't put the cart before the horse!
- Solution:
  1. Create socket at configuration time
  2. Hook trace source then
  3. Pass this socket object to system during simulation time

Next: `fifth.cc` walkthrough

Overview of `fifth.cc`

- Dumbbell topology, point-to-point network, like `first.cc`



- We will create our own application and socket
  - So we can access socket at configuration time
  - No helper, so we'll have to do the work manually
  - Connect to `CongestionWindow` trace source in sender socket
- Introduce errors into the channel between nodes
  - Dropped packets ⇒ interesting behavior in congestion window

Creating our own application: the MyApp class

```
class MyApp : public Application
{
public:

  MyApp ();
  virtual ~MyApp();

  void Setup (Ptr<Socket> socket, Address address,
              uint32_t packetSize, uint32_t nPackets, DataRate dataRate);

private:
  virtual void StartApplication (void);
  virtual void StopApplication (void);

  void ScheduleTx (void);
  void SendPacket (void);

  Ptr<Socket>     m_socket;
  Address         m_peer;
  uint32_t        m_packetSize;
  uint32_t        m_nPackets;
  DataRate        m_dataRate;
  EventId         m_sendEvent;
  bool            m_running;
  uint32_t        m_packetsSent;
};
```

Initializes member variables

But this is the important bit: we will be able to
- Create socket
- Hook its CongestionWindow trace source
- Pass the socket to the application

All this at configuration time!

Creating our own application: the MyApp class

```
class MyApp : public Application
{
public:

  MyApp ();
  virtual ~MyApp();

  void Setup (Ptr<Socket> socket, Address address,
              uint32_t packetSize, uint32_t nPackets, DataRate dataRate);

private:
  virtual void StartApplication (void);
  virtual void StopApplication (void);

  void ScheduleTx (void);
  void SendPacket (void);

  Ptr<Socket>     m_socket;
  Address         m_peer;
  uint32_t        m_packetSize;
  uint32_t        m_nPackets;
  DataRate        m_dataRate;
  EventId         m_sendEvent;
  bool            m_running;
  uint32_t        m_packetsSent;
};
```

We also need to override these with our own implementations that will be called by the simulator to start and stop

Creating our own application: the MyApp class

```
class MyApp : public Application
{
public:

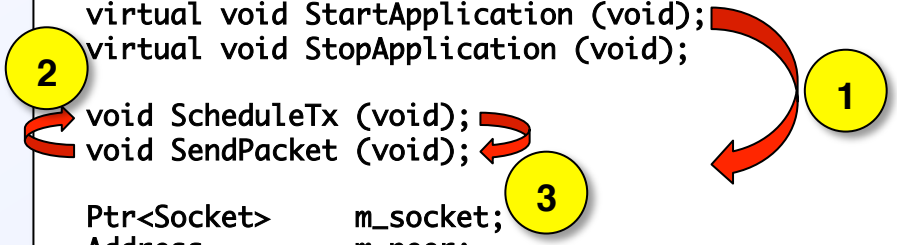
  MyApp ();
  virtual ~MyApp();

  void Setup (Ptr<Socket> socket, Address address,
              uint32_t packetSize, uint32_t nPackets, DataRate dataRate);

private:
  virtual void StartApplication (void);
  virtual void StopApplication (void);

  void ScheduleTx (void);
  void SendPacket (void);

  Ptr<Socket>     m_socket;
  Address         m_peer;
  uint32_t        m_packetSize;
  uint32_t        m_nPackets;
  DataRate        m_dataRate;
  EventId         m_sendEvent;
  bool            m_running;
  uint32_t        m_packetsSent;
};
```



1. StartApplication **calls** SendPacket
2. SendPacket **calls** ScheduleTx
3. ScheduleTx **set up next** SendPacket **call**
4. ...
5. **Until** StopApplication

The trace sinks

- We want to trace 2 types of events
  - Updates to the congestion window:

```
static void CwndChange (uint32_t oldCwnd, uint32_t newCwnd)
{
  NS_LOG_UNCOND (Simulator::Now ().GetSeconds () << "\t" << newCwnd);
}
```

  - Dropped packets

```
static void RxDrop (Ptr<const Packet> p)
{
  NS_LOG_UNCOND ("RxDrop at " << Simulator::Now ().GetSeconds ());
}
```

Introducing errors in the channel

Determines which packets will not be received due to transmission errors, corresponding to underlying

- Distribution = random variable
- Rate ↔ mean duration between errors
- Unit = per-bit, per-byte, or per-packet

```
Ptr<RateErrorModel> em = CreateObjectWithAttributes<RateErrorModel> (
      "RanVar", RandomVariableValue (UniformVariable (0., 1.)),
      "ErrorRate", DoubleValue (0.00001));

devices.Get (1)->SetAttribute ("ReceiveErrorModel", PointerValue (em));
```

Will cause randomly dropped packets in the receiver device

Setting the application on the receiver node

```
uint16_t sinkPort = 8080;
Address sinkAddress (InetSocketAddress (interfaces.GetAddress (1), sinkPort));
PacketSinkHelper packetSinkHelper ("ns-3::TcpSocketFactory",
                                   InetSocketAddress (Ipv4Address::GetAny (), sinkPort));
ApplicationContainer sinkApps = packetSinkHelper.Install (nodes.Get (1));
sinkApps.Start (Seconds (0.));
sinkApps.Stop (Seconds (20.));
```

- `PacketSink` receives and consumes traffic generated to an IP address and port
- `PacketSinkHelper` creates sockets using an "object factory"
  - Object factories are used to mass produce similarly configured objects
  - Factory method doesn't require you to know the type of the objects created

Connecting the sender's socket, and connecting the trace source

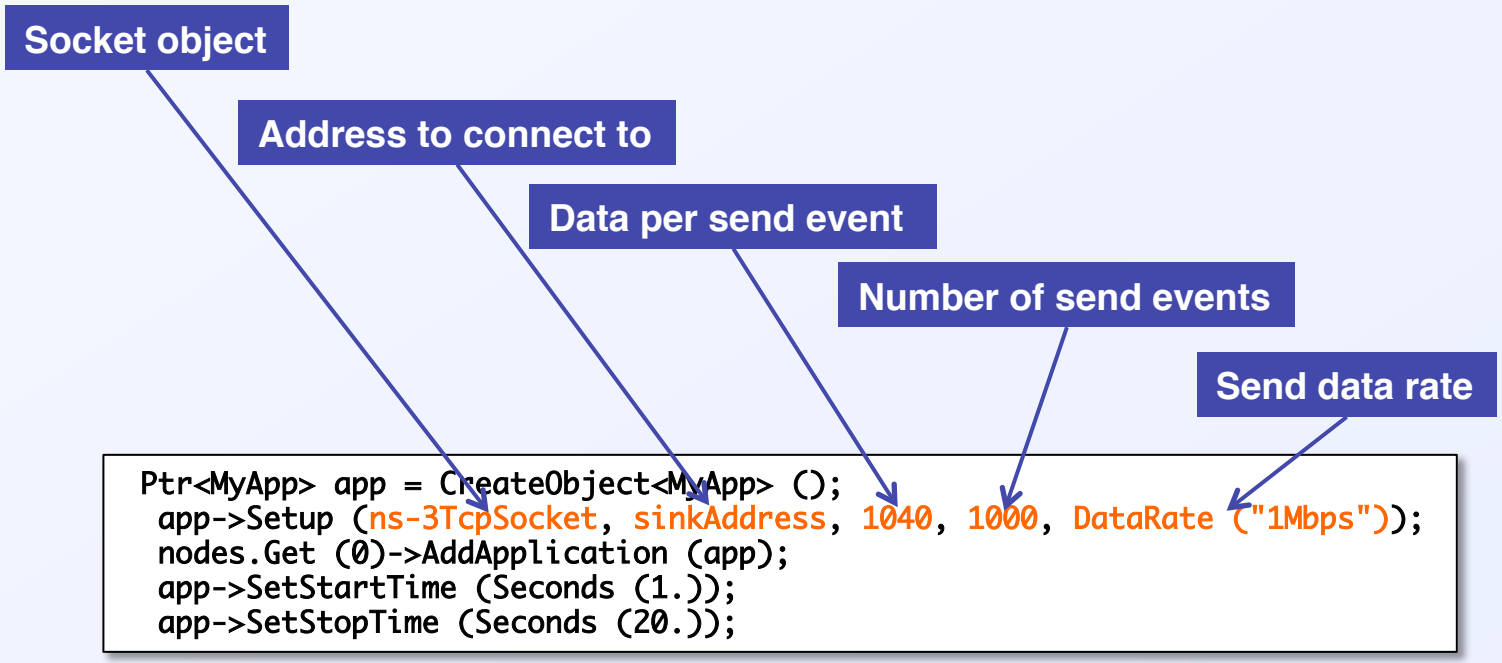
Another way of creating a socket using a socket factory

```
Ptr<Socket> ns-3TcpSocket = Socket::CreateSocket (nodes.Get (0), TcpSocketFactory::GetTypeId ());
ns-3TcpSocket->TraceConnectWithoutContext ("CongestionWindow", MakeCallback (&CwndChange));
```

This should look familiar by now

Because we created our own app and socket at configuration time we can hook into its `CongestionWindow` trace source

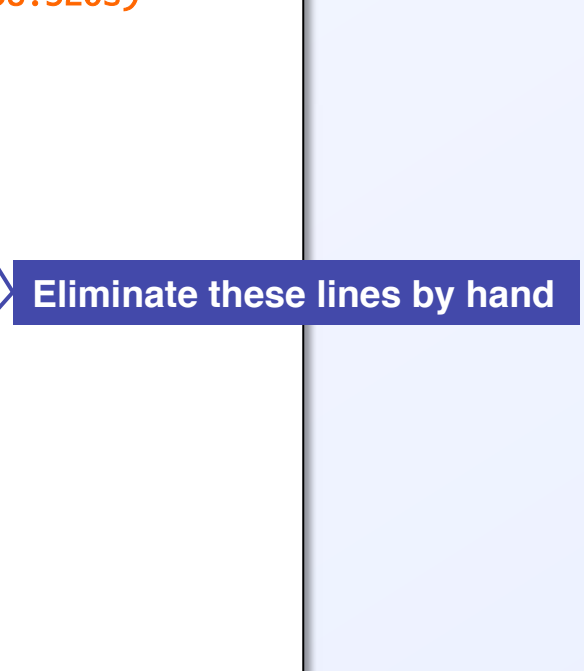
Setting up the application on the sender node



Running `fifth.cc`: text output

```
$ ./waf -run scratch/myfifth > cwnd.dat 2>&1
```

```
Waf: Entering directory `/mypath/ns-3-dev/build'
Waf: Leaving directory `/mypath/ns-3-dev/build'
'build' finished successfully (1m58.520s)
1       536
1.00919 1072
1.01511 1608
1.02163 2144
1.02995 2680
1.03827 3216
1.04659 3752
1.05491 4288
1.06323 4824
1.07155 5360
1.07987 5896
1.08819 6432
1.09651 6968
1.10483 7504
1.11315 8040
1.12147 8576
1.12979 9112
RxDrop at 1.13692
1.13811 9648
1.15475 2900
1.15563 3436
          ⋮
```



Running `fifth.cc`: plotting the results

Original by W. Richard Stevens

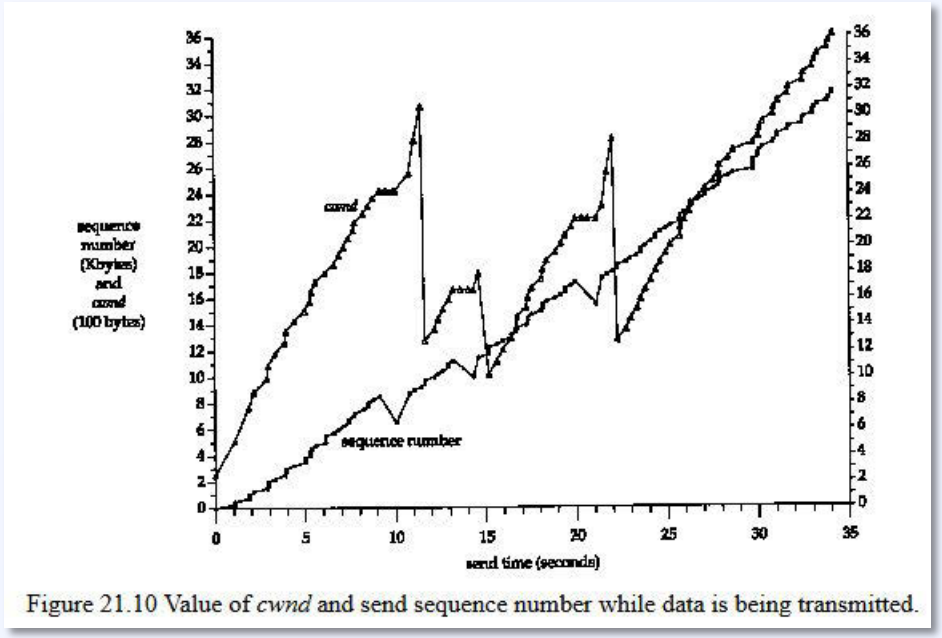
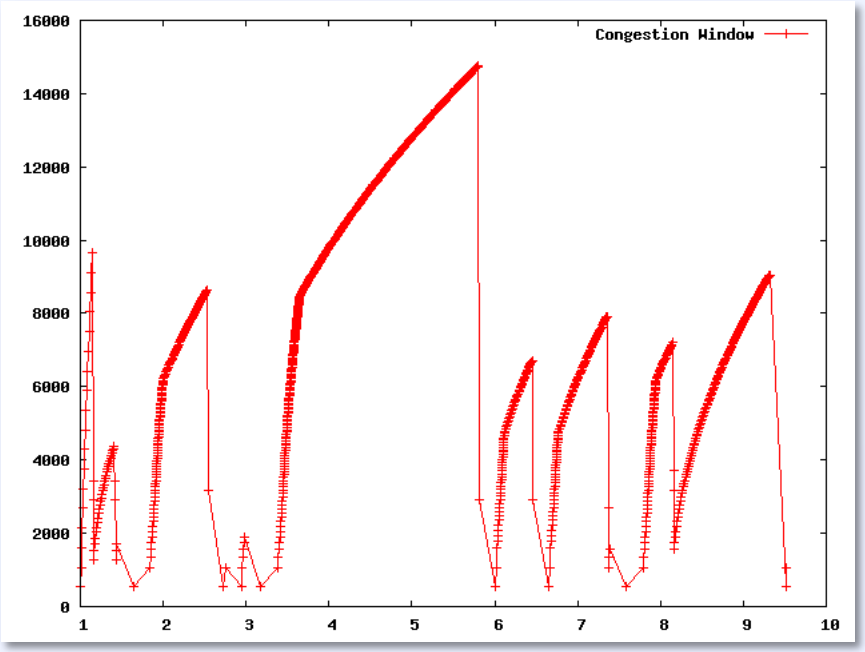


Figure 21.10 Value of *cwnd* and send sequence number while data is being transmitted.

Our result, using gnuplot



That's nice, but…

- Remember after

```
$ ./waf –run scratch/myfifth > cwnd.dat 2>&1
```

- We had to edit the file by hand to remove "junk" lines…

- But we said tracing gives you control over output format
- Is there a cleaner way to produce the output we need?
- Yes! Use trace helpers

Let's tweak `fifth.cc` to produce cleaner output ⇒ `sixth.cc`

A sixth.cc walkthrough: CwndChange callback

- **Modify the callback function:**

```
static void CwndChange (Ptr<OutputStreamWrapper> stream, uint32_t oldCwnd, uint32_t newCwnd)
{
  NS_LOG_UNCOND (Simulator::Now ().GetSeconds () << "\t" << newCwnd);
  *stream->GetStream () << Simulator::Now ().GetSeconds () << "\t"
                        << oldCwnd << "\t" << newCwnd << std::endl;
}
```

Added to fifth.cc

Formatted output to the stream

- **Add lines in the main to create stream:**

Filename attached to stream

```
  AsciiTraceHelper asciiTraceHelper;
  Ptr<OutputStreamWrapper> stream = asciiTraceHelper.CreateFileStream ("sixth.cwnd");
  ns-3TcpSocket->TraceConnectWithoutContext ("CongestionWindow",
                                             MakeBoundCallback (&CwndChange, stream));
```

Causes the stream argument to be added to the function callback

A sixth.cc walkthrough: RxDrop callback

- **Modify the callback function:**

```
static void RxDrop (Ptr<PcapFileWrapper> file, Ptr<const Packet> p)
{
  NS_LOG_UNCOND ("RxDrop at " << Simulator::Now ().GetSeconds ());
  file->Write (Simulator::Now (), p);
}
```

Formatted output to the pcap file

Added to fifth.cc

- **Add lines in the main to create stream:**

Filename attached to file

```
  PcapHelper pcapHelper;
  Ptr<PcapFileWrapper> file = pcapHelper.CreateFile ("sixth.pcap", std::ios::out, PcapHelper::DLT_PPP);
  devices.Get (1)->TraceConnectWithoutContext ("PhyRxDrop", MakeBoundCallback (&RxDrop, file));
```

Causes the file argument to be added to the function callback

Running `sixth.cc`

```
$ ./waf -run scratch/mysixth
```

Console

```
Waf: Entering directory `…
Waf: Leaving directory `…
'build' finished successfully (6.002s)
1       536
1.00919 1072
1.01511 1608
1.02163 2144
1.02995 2680
1.03827 3216
1.04659 3752
1.05491 4288
1.06323 4824
1.07155 5360
1.07987 5896
1.08819 6432
1.09651 6968
1.10483 7504
1.11315 8040
1.12147 8576
1.12979 9112
RxDrop at 1.13692
1.13811 9648
1.15475 2900
1.15563 3436
    ⋮
```

sixth.cwnd

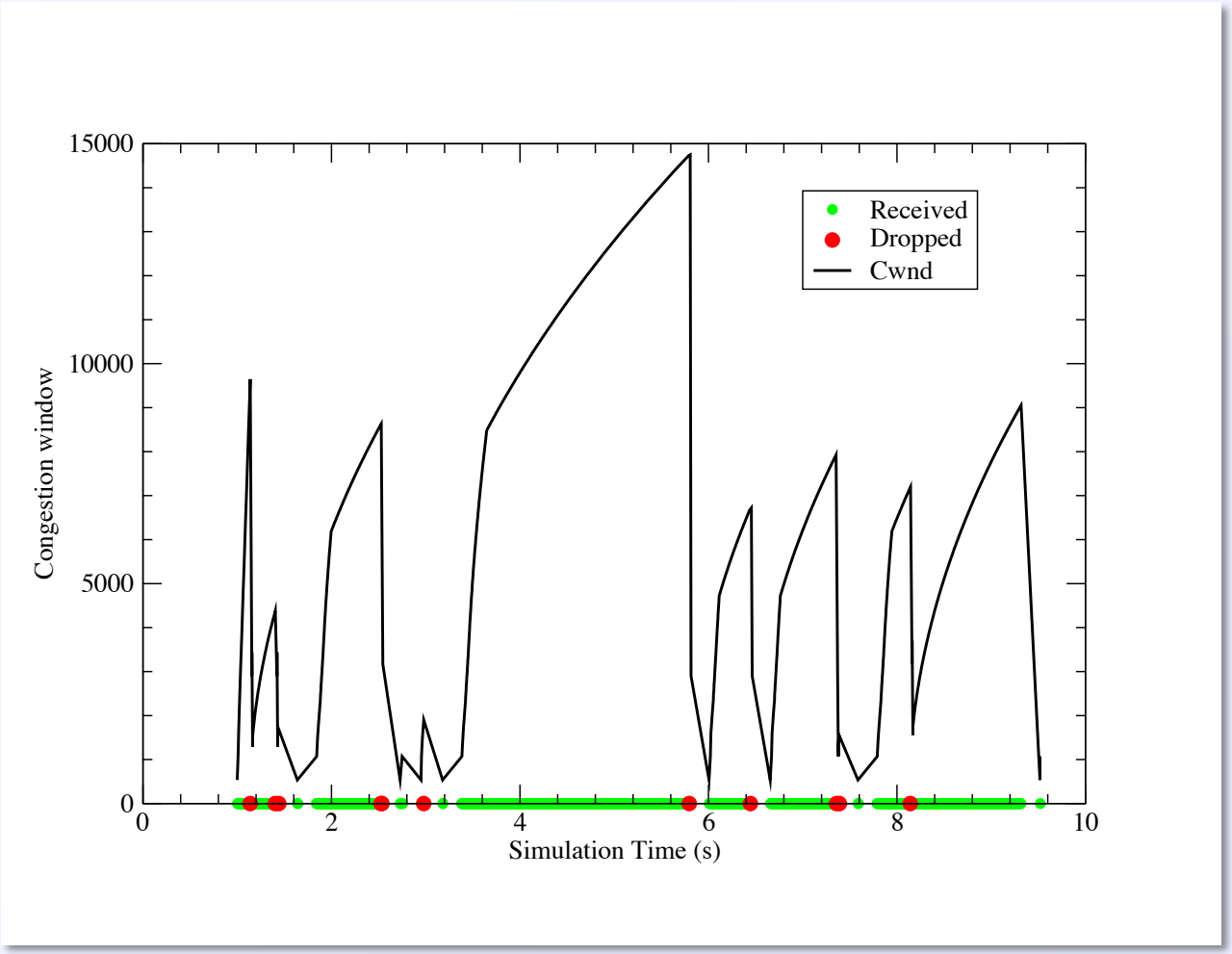
```
1       0       536
1.00919 536     1072
1.01511 1072    1608
1.02163 1608    2144
1.02995 2144    2680
1.03827 2680    3216
1.04659 3216    3752
1.05491 3752    4288
1.06323 4288    4824
1.07155 4824    5360
1.07987 5360    5896
1.08819 5896    6432
1.09651 6432    6968
1.10483 6968    7504
1.11315 7504    8040
1.12147 8040    8576
1.12979 8576    9112
1.13811 9112    9648
⋮
```

sixth.pcap

```
reading from file sixth.pcap, link-type PPP (PPP)
1.136918 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 17177:17681, ack 1, win 65535, le
1.403158 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 33280:33784, ack 1, win 65535, le
1.440505 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 37440:37944, ack 1, win 65535, le
2.525484 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 173144:173680, ack 1, win 65535,
2.534678 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 174720:175224, ack 1, win 65535,
2.977574 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 180552:181088, ack 1, win 65535,
5.796117 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 582400:582904, ack 1, win 65535,
6.445077 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 663520:664024, ack 1, win 65535,
7.359404 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 777384:777920, ack 1, win 65535,
7.389304 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 781040:781544, ack 1, win 65535,
8.141483 IP 10.1.1.1.49153 > 10.1.1.2.8080: Flags [.], seq 875144:875680, ack 1, win 65535,
```

Just for fun: what happens to uncorrupted packets?

PhyRxEnd: Trace source indicating a packet has been completely received by the device



Using trace helpers

- We've encountered trace helpers before

```
pointToPoint.EnablePcapAll ("second");
pointToPoint.EnablePcap ("second", p2pNodes.Get (0)->GetId (), 0);
csma.EnablePcap ("third", csmaDevices.Get (0), true);
pointToPoint.EnableAsciiAll (ascii.CreateFileStream ("myfirst.tr"));
```

- What other trace helpers are available?
- How do we use them?
- What do they have in common?

Two categories of trace helpers

- Device helpers
  - Trace is enabled for node/device pair(s)
  - Both pcap and ascii traces provided
  - Conventional filenames: `<prefix>-<node id>-<device id>`
- Protocol helpers
  - Trace is enabled for protocol/interface pair(s)
  - Both pcap and ascii traces provided
  - Conventional filenames: `<prefix>-n<node id>-i<interface id>`
    - "`n`" and "`i`" to avoid filename collisions with node/device traces

ns-3 uses “mixin” classes to ensure tracing works the same way across all devices or interfaces

- **Mixin classes in ns-3 (see Doxygen for more info):**

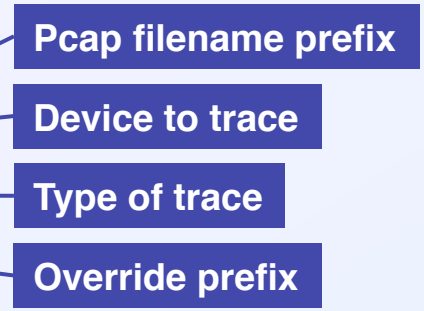
	PCAP	ASCII
Device Helper	PcapHelperForDevice	AsciiTraceHelperForDevice
Protocol Helper	PcapHelperForIpv4	AsciiTraceHelperForIpv4

- **These mixin classes each provide a single virtual method to enable trace**
  - **All device or protocols must implement this method**
  - **All other methods of the mixin class call this one method**
  - **Provides consistent functionality across different devices & interfaces**

The PcapHelperForDevice mixin class

- Every device must implement

```
virtual void EnablePcapInternal (std::string prefix,
                                 Ptr<NetDevice> nd,
                                 bool promiscuous,
                                 bool explicitFilename) = 0;
```



- All other methods of `PcapHelperForDevice` call this one

⇒ Consistency across devices

Pcap Tracing Device Helper: EnablePcap methods

- EnablePcap for various node/device pair(s)
  - Provide Ptr<NetDevice>
  - Provide device name using the ns-3 object name service

```
Names::Add ("server" ...);
Names::Add ("server/eth0" ...);a
...
helper.EnablePcap ("prefix", "server/ath0");
```

  - Provide a NetDeviceContainer
  - Provide a NodeContainer
  - Provide integer node and device ids
- Enable pcap tracing for all devices in the simulation

```
helper.EnablePcapAll ("prefix");
```

Pcap Tracing Device Helper: filename selection

- By convention: `<prefix>-<node id>-<device id>.pcap`
- Can use the ns-3 object name service to replace ids with meaningful names e.g.,

```
prefix-21-1.pcap
```

```
Names::Add("server1",serverNode);
Names::Add("server1/eth0",serverDevice);
```

```
prefix-server1-eth0.pcap
```

- You can override the naming convention, e.g.

```
void EnablePcap(std::string prefix,
                Ptr<NetDevice> nd,
                bool promiscuous,
                bool explicitFilename);
```

Set this to true
prefix becomes filename

Ascii Tracing Device Helpers

- The mixin class is `AsciiTraceHelperForDevice`
  - All device implement virtual `EnableAsciiInternal` method
  - All other methods of `AsciiTraceHelperForDevice` will call this one
- Can provide `EnableAscii` with `Ptr<NetDevice>`, string from name service, `NetDeviceContainer`, `NodeContainer`, integer node/device ids
- Or `helper.EnableAsciiAll("prefix");`
- Can also dump ascii traces to a single common file, e.g.,

```
Ptr<NetDevice> nd1;
Ptr<NetDevice> nd2;
...
Ptr<OutputStreamWrapper> stream = asciiTraceHelper.CreateFileStream ("trace-file-name.tr");
...
helper.EnableAscii (stream, nd1);
helper.EnableAscii (stream, nd2);
```

- So there are twice as many trace methods as for pcap

Ascii Tracing Device Helpers: filename selection

- By convention: `<prefix>-<node id>-<device id>.tr`
- Using ns-3 object name service, can assign names to the id, then e.g.
  - "`prefix-21-1.tr`" → "`prefix-server-eth0.tr`"
- Many `EnableAscii` methods offer a `explicitFilename` option
  - Set to true ⇒ override naming convention, use your own file name

Pcap Tracing Protocol Helpers

- The mixin class is `PcapHelperForIpv4`
  - All device implement virtual `EnablePcapIpv4Internal` method
  - All other methods of `PcapHelperForIpv4` will call this one
- Can provide `EnablePcapIpv4` with `Ptr<Ipv4>`, string from name service, `Ipv4InterfaceContainer`, `NodeContainer`, integer node/device ids
- Or `helper.EnablePcapIpv4All("prefix");`
- Filename selection
  - Convention is `<prefix>-n<node id>-i<interface id>.pcap`
  - Can also use the ns-3 object name service clarity
  - `explicitFilename` parameter lets you impose your own filenames

Ascii Tracing Protocol Helpers

- The mixin class is `AsciiTraceHelperForIpv4`
  - All device implement virtual `EnableAsciiIpv4Internal` method
  - All other methods of `AsciiTraceHelperForIpv4` will call this one
- Can provide `EnableAsciiIpv4` with `Ptr<Ipv4>`, string from name service, `Ipv4InterfaceContainer`, `NodeContainer`, integer node/device ids
- Or `helper.EnableAsciiIpv4All("prefix");`
- Can also dump ascii traces to a single common file
  - So there are twice as many trace methods as for pcap
- Filename selection
  - Convention is `<prefix>-n<node id>-i<interface id>.pcap`
  - Can also use the ns-3 object name service clarity
  - `explicitFilename` parameter lets you impose your own filenames

Conclusion

- ns-3 is very powerful/comprehensive
- Lots of tools for you to use
  - Helpers
  - Containers
  - Logging
  - Tracing
  - Models
- Doxygen is your friend!

Practice! Practice! Practice!