How to Use the Netbed (Emulab++) Network Testbeds

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SIGCOMM Tutorial

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So, you've built the next great {distributed system, network protocol, P2P app, etc.}

But, you need to test and evaluate it

Netbed Can Help

- At its base: machines with accounts (even root)
- We configure networks, but control is yours
  - Do whatever you want on/to nodes
  - Even install a new OS!
- All the amenities of home
  - Console access
  - Power control
- Incorporates other experimental environments
  - Wide-area nodes, simulated nodes
  - Use what makes the most sense for your experiment
- Simple stuff is simple; hard stuff (anything) is possible

So, Show Me!

Let’s set up an experiment:

http://www.netbed.org/

Why?

- “We evaluated our system on five nodes.”
  -job talk from university with 300-node cluster
- “We evaluated our Web proxy design with 10 clients on 100Mbit ethernet.”
- “Simulation results indicate ...”
- “Memory and CPU demands on the individual nodes were not measured, but we believe will be modest.”
- “You have to know the right people to get access to the cluster.”
- “The cluster is hard to use.”
- “We obtained guest accounts through 13 friends around the world to carry out our Internet measurements.”

Common Misconceptions

- Unfamiliar environment
  - No, you typically get standard hardware and software
- Like a simulation, it must “run on its own”
  - No, you ask for just the features you want
- Lots of NS expertise required
  - No, there’s a Java GUI for experiment configuration
  - No, configuration can be done with a subset of NS and cut-and-paste
- “Just a cluster”
  - No, configures network to emulate custom topologies
- “Just emulation”
  - No, support for real wide-area nodes & simulated nodes

What's a Node? What's a Router? (misconceptions)

- Physical hardware:
  - PC (local or remote)
  - (StrongARM box: in past)
  - (IXP1200, a specialized network processor: soon)
  - (Wireless: future)
- Virtual node:
  - Router (network emulation)
  - "Middlebox" (distributed system)
  - End host
  - A piece of a distributed node

What is Netbed / Emulab?

- A time- and space-shared platform for research, development, and education in distributed systems and networks
- A large software system
- Machines with configurable connectivity
- Emulab is the primary *emulation* portion of Netbed
  - www.emulab.net (Utah, 168 nodes, public)
  - uky.emulab.net (Kentucky, 48 nodes)
  - Georgia Tech (~50 nodes, soon)
  - ….

What is it (cont'd): Emulation Portion

- A configurable and controllable network emulator in a room
  - Utah Emulab today: 168 nodes, 1646 cables, 4 big switches
  - virtualizable topology, links, node software
- Bare hardware with lots of tools
- A controllable virtual world for distributed systems and networks

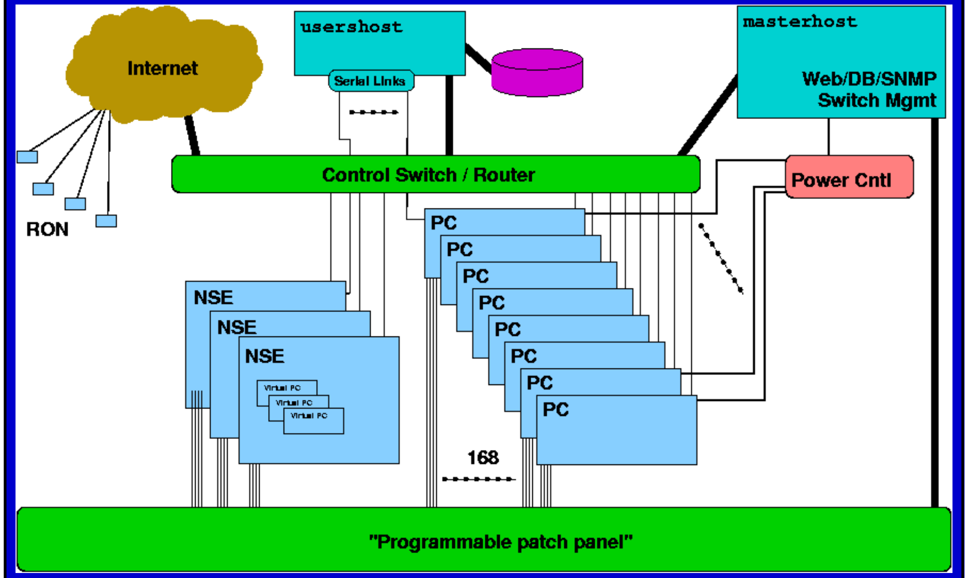
What is it? (cont'd)

- … a base for physically distributed network testbeds and virtual (overlay) networks
- A way to get access to nodes all over the world
- An instrument for experimental CS research
- Universally available to any remote experimenter
- Simple to use

Utah Netbed Site

Kentucky Netbed Site

Distributed (Wide-Area) Nodes



Node Types In Utah Emulab Today

- pc600 (40)
  - 600MHz processor
  - 256 MB RAM
  - 13 GB IDE disks
- pc850 (128)
  - 850MHz processor
  - 512 MB RAM
  - 40 GB IDE disks

On With How to Use It

Getting Started

- **Visit the website at www.netbed.org**
- **Apply to *start* or *join* a *project***
  - Creates a new user account
- **Create an *experiment***
  - Topology/configuration specified with
    - a Java GUI, or
    - an *ns* file
- **Start using your experiment!**

www.netbed.org (emulab.net)

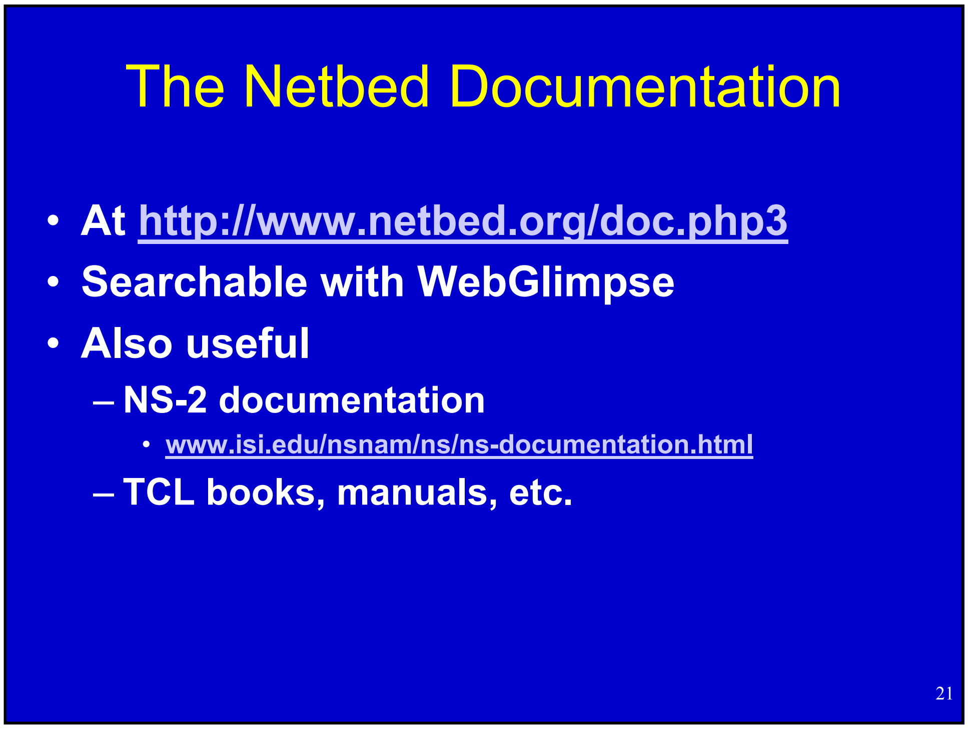
- **Most work can be done through our web interface**
  - Beginning/ending experiments
  - Applying for/approving access
  - Controlling nodes
- **Searchable documentation**
- **Secure access using https**

A “Project”

- **Central administrative entity**
- **Started by a faculty member or senior student**
  - Submitted through web interface
  - User account gets created for experiment leader
- **Approval of project users delegated to leader**
  - Saves on administrative overhead
  - Project leader responsible for users' behaviour
- **Project gets its own disk space**

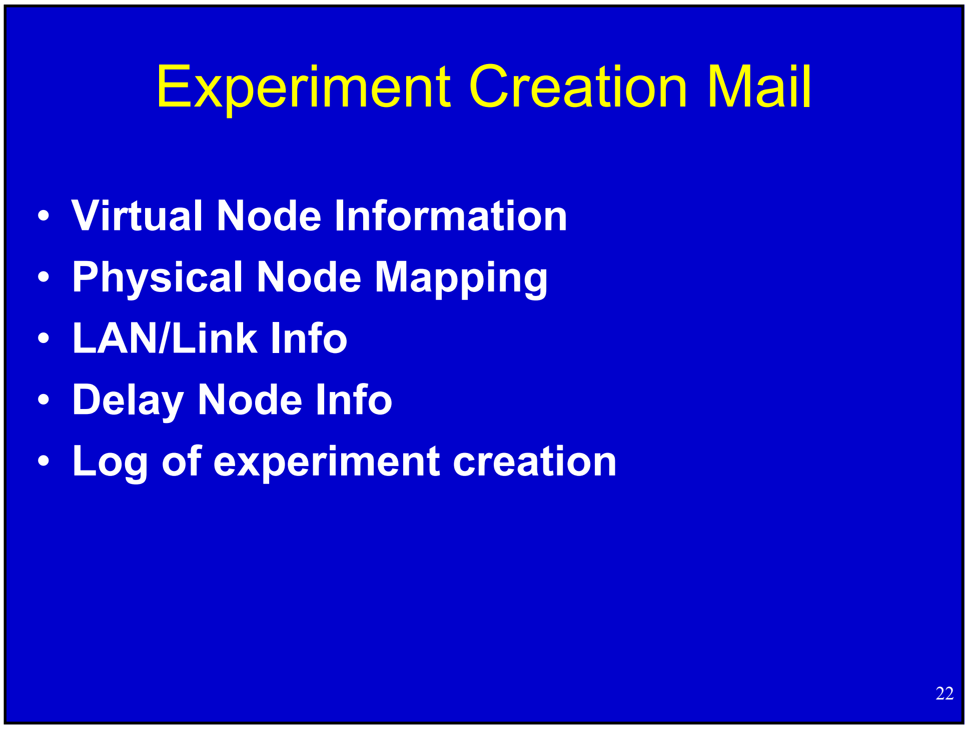
An “Experiment”

- **Central operational entity**
- **Represents network configuration, including**
  - Network links
  - Node configuration
  - May include traffic generations, event stream
  - May simply be some allocated machines!
- **Created with an *ns* file or a simple GUI**
- **Started through web interface**
- **Mail sent when setup is complete**



The Netbed Documentation

- At http://www.netbed.org/doc.php3
- Searchable with WebGlimpse
- Also useful
  - NS-2 documentation
    - www.isi.edu/nsnam/ns/ns-documentation.html
  - TCL books, manuals, etc.



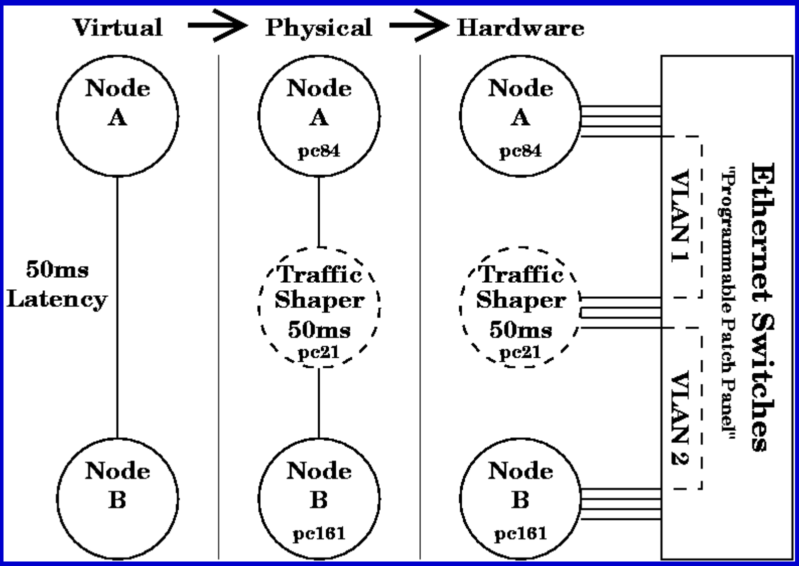
Experiment Creation Mail

- Virtual Node Information
- Physical Node Mapping
- LAN/Link Info
- Delay Node Info
- Log of experiment creation

VLANs and Delay Nodes

- Isolation done with Virtual LANs (VLANs) on our switches
- Traffic shaping done with transparent bridges
  - Invisible to nodes
  - Regular nodes running FreeBSD
  - dummynet used for traffic shaping
  - Listens for events related to its links

VLANs and Delay Nodes - Diagram



Introduction to Using Your Experiment

Nodes

- **Logging into nodes**
  - ssh access
    - Add public keys via our web interface
  - Fully-qualified names
- **Shared NFS home directory**
- **Root access via sudo**
- **Testbed-specific configuration in `/etc/testbed`**
- **You're free to do whatever you want to them – disks get reloaded afterwards**

Web

- **Web control of running experiments**
  - View experiment report
  - Swap in/out
  - View NS file and visualization
- **Node control**
  - Set OS
  - Add RPMs, tarballs, startup scripts, etc.
  - Reboot node
  - Access to node serial console

users.emulab.net

- **Commands available on users.emulab.net**
  - node_reboot -reboot/power cycle
  - os_load - recover scrogged disks
  - portstats - see switch port counters
- **‘console’ - serial console access**
- **Disk space:**
  - /users – small stuff
  - /proj – bigger stuff (shared among members of the project)

Serial Consoles

- Link on node page
- Requires some setup
  - Download `tiptunnel` (Windows, Linux, FreeBSD binaries available)
  - Install wherever convenient
  - Associate file type with downloaded binary
- All output logged on `users.emulab.net`
  - `/var/log/tiplogs/<physid>.run`

NS Specifics

Audience Familiarity With NS

- Use it all the time?
- Use it a little?
- Have used TCL, but not NS?
  - NS scripts are written in TCL
- Never used either?

Boilerplate

- Statements required in every Netbed NS file
- **`set $ns [new Simulator]`**
  - Creates a new NS “simulator object”
- **`source tb_compat.tcl`**
  - Load testbed-specific commands
  - Stub version provided for running in NS
- **`$ns run`**
  - In NS, runs the simulation

Nodes – Netbed-Specific Commands

- `tb-set-node-os nodeA FBSD-STD`
  - Set OS. Currently supported:
    - `FBSD-STD`
    - `RHL-STD`
    - `<your own>`
- `tb-set-hardware nodeA pc600`
  - Pick specific PC type: `pc600/pc850`
  - `pcvron/pcvwa`

Links

- `$ns duplex-link $nodeA $nodeB 100Mb 0ms DropTail`
  - Set bandwidth and/or latency
  - Queuing types: DropTail, RED, GRED
- **Naming links:**
  - `set link0 [$ns duplex-link ...]`
  - Always name your links
- `tb-set-link-loss $link0 0.05`
  - Ratio of lost packets: 1.0 means drop all packets

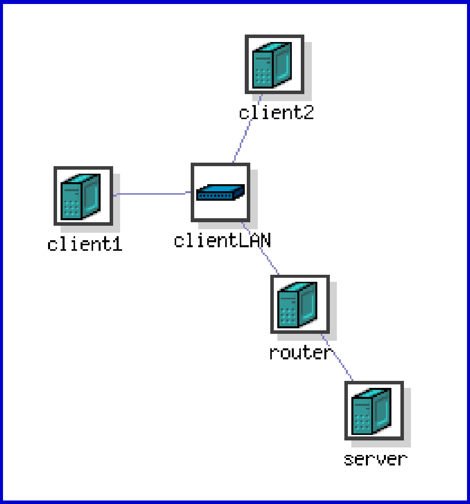
LANs

- `$ns make-lan "$nodeA $nodeB $nodeC" 100Mb 0ms`
- **Naming works the same as with links**
- **Setting packet loss on a LAN**
  - `tb-set-lan-loss $lan0 0.01`
- **Setting different characteristics for a single node:**
  - `tb-set-node-lan-delay $lan0 $nodeA 40ms`
  - `tb-set-node-lan-bandwidth $lan0 $nodeA 20Mb`
- **Unlike links, no queuing discipline**

Routing

- **Types of routing**
  - Manual - You specify
  - Static - Computed by testbed software
  - Session – Dynamic (OSPF), using gated
- `$ns rtproto Static`
  - Set routing type
- `$client add-route $server $router`
  - Adds routes when using Manual routing

LAN Example



LAN Example NS File

```
set ns [new Simulator]
source tb_compat.tcl

$ns rtproto Static

set server  [$ns node]
set router  [$ns node]
set client1 [$ns node]
set client2 [$ns node]

set serverLink [$ns duplex-link $router $server 1.5Mb 30ms DropTai
tb-set-link-loss $serverLink 0.01

set clientLAN [$ns make-lan "$client1 $client2 $router" 100Mb 0ms]

$ns run
```

Traffic Generation

- Standard NS
- 3 Parts
  - Agent: TCP/UDP socket
    - Gets attached to a node
  - Application
    - Generates traffic, attached to an agent
  - Sink
    - Connected to the agent, just discards traffic
- Has to be started with an event

Traffic Generation (cont'd)

```
set tcp0 [new Agent/TCP]
$ns attach-agent $nodeA $tcp0

set cbr0 [new Application/Traffic/CBR]
$cbr0 set packetSize_ 1200
$cbr0 set rate_ 100Mb
$cbr0 attach-agent $tcp0

set null0 [new Agent/Null]
$ns attach-agent $nodeB $null0

$ns connect $tcp0 $null0

$ns at 1 "$cbr0 start"
```

Program Objects

```
set prog0 [new Program $ns]
$prog0 set node $nodeA
$prog0 set command "/users/ricci/dostuff args"

$ns at 10 "$prog0 start"
$ns at 20 "$prog0 stop"
$ns at 30 "$prog0 start"
```

Constants

- **Makes it easy to change operating systems**
  - `set OS FBSD45-STD`
  - `tb-set-node-os nodeA $OS`
  - `tb-set-node-os nodeB $OS`
- **Makes it easy to set node types**
- **… to set bandwidth**
- **… to set latency**
- **… etc.**

Loops

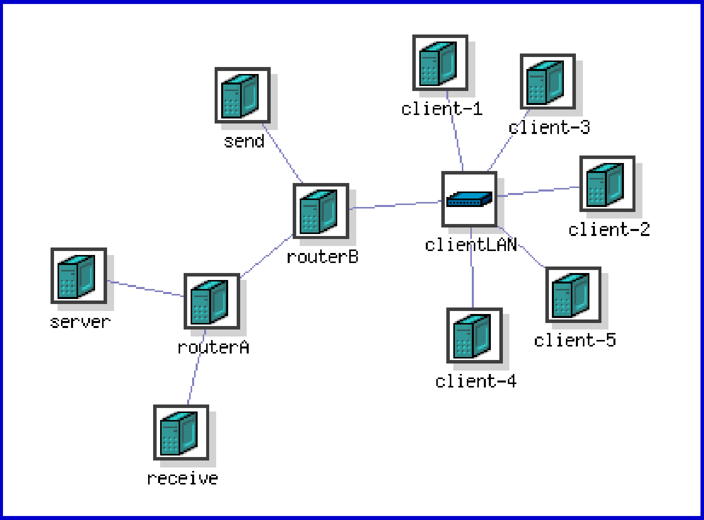
```
set num_nodes 20

for {set i 1} {i <= $num_pcs} {incr i} {
     set pc($i) [$ns node]
     tb-set-node-os $pc($i) FBSD-STD
     append lan_string "$pc(${i}) "
}

set lan0 [$ns make-lan "$lan_string” 100Mb]
```

$pc($i) gets converted to “pc-$i” in node names

Large Example



Large Example NS File

```
set ns [new Simulator]
source tb_compat.tcl
$ns rtproto Static

set num_clients 5
set server_os FBSD-STD
set client_os RHL-STD

set server  [$ns node]
set routerA [$ns node]
set routerB [$ns node]
set send    [$ns node]
set receive [$ns node]
for {set i 1} {$i <= $num_clients} {incr i} {
        set client($i) [$ns node]
        tb-set-node-os $client($i) $client_os
        append lan_string "$client(${i}) "
}
```

Large Example NS File (cont’d)

```
tb-set-node-os $server $server_os

set routerLink  [$ns duplex-link $routerA $routerB 100Mb 0ms DropTail]
set serverLink  [$ns duplex-link $routerA $server  100Mb 0ms DropTail]
set sendLink    [$ns duplex-link $routerB $send    100Mb 0ms DropTail]
set receiveLink [$ns duplex-link $routerA $receive 100Mb 0ms DropTail]
set clientLAN   [$ns make-lan "$lan_string $routerB" 100Mb 0ms]

set tcp0 [new Agent/TCP]
$ns attach-agent $send $tcp0
set cbr0 [new Application/Traffic/CBR]
$cbr0 set packetSize_ 1200
$cbr0 set rate_ 50Mb
$cbr0 attach-agent $tcp0

set null0 [new Agent/Null]
$ns attach-agent $receive $null0
$ns connect $tcp0 $null0

$ns at 1 "$cbr0 start”
```

Large Example NS File (cont'd)

```
set server_prog [new Program $ns]
$server_prog set node $server
$server_prog set command "/proj/testbed/bin/serverprogram"
$ns at 1 "$server_prog start"

$ns run
```

RPMs and Tarfiles

- `tb-set-node-rpms $node a.rpm`
  - Convenient way to install Linux packages
  - Installation is forced
  - Can specify multiple RPMs on one line
- `tb-set-node-tarfiles $node`
  - Arguments: alternating directory and tarball paths
  - Changes to directory before untarring
  - Untars as root (owner in tarfile still applies)

Startup Commands

- **`tb-set-node-startup $node "command"`**
  - Script should be in home or project directory
  - Command is run as experiment creator
- Differences from Program Objects
  - Executed every time node boots
  - No synchronization
- Uses
  - Tweak node configuration (routing, etc.)
  - Run services

Setting Node IP Addresses

- Assigned for you automatically if omitted
  - Recommended
  - Uses a deterministic algorithm
- **`tb-set-ip $node IP`**
  - Use only for single-interface nodes
- **`tb-set-ip-link $node $link IP`**
- **`tb-set-ip-lan $node $lan IP`**

Existing Tools

- **Can use existing topology generators**
  - Tiers
  - GT-ITM
  - BRITE
- **Anything that exports NS**

More Netbed Control

Swapping an Experiment

- Release hardware resources without ending experiment - OS analogy
- Experiment information is maintained in DB
- Can easily swap back in - a few minutes
- We typically have more experiments swapped out than in, at any point in time.
- Role of node state in determining & specifying swappability

Swapping an Experiment – Soft State

- Soft state is the part not saved on swapout
- It includes
  - Contents of nodes' local disks
  - Effects of dynamic events (next slides)
- Hard state includes
  - Things in your home directory
  - Anything given in the NS file
- Disk contents can be saved in disk images

Event System - Overview

- **Used for distributed control**
  - Starting/stopping programs
  - Controlling traffic
  - Changing link characteristics
- **Underlying publish/subscribe system**
- **Static events can be injected by NS scripts**
- **Dynamic events can be injected by hand**
- **Users can write their own programs that hook into the event system**

Event System – Static Events from NS Scripts

- **Link control**
  - `$ns at 10 "$link0 down"`
  - `$ns at 20 "$link0 delay 5.5ms"`
- **Traffic control**
  - `$ns at 5.5 "$cbr0 start"`
- **Program control**
  - `$ns at 1 "$prog0 start“`
- **Loops, of course…**

Event System – Dynamic Events

- tevc
  - Available on nodes or users.emulab.net
  - Arguments
    - "`-e pid/eid`" (Only required if used on `users`)
    - Time (now, +seconds, or [[[[yy]mm]dd]HH]MMss)
    - Object
    - Event
- Examples
  - tevc now cbr0 start
  - tevc –e testbed/foo +30 link0 set delay=50

Virtual Types

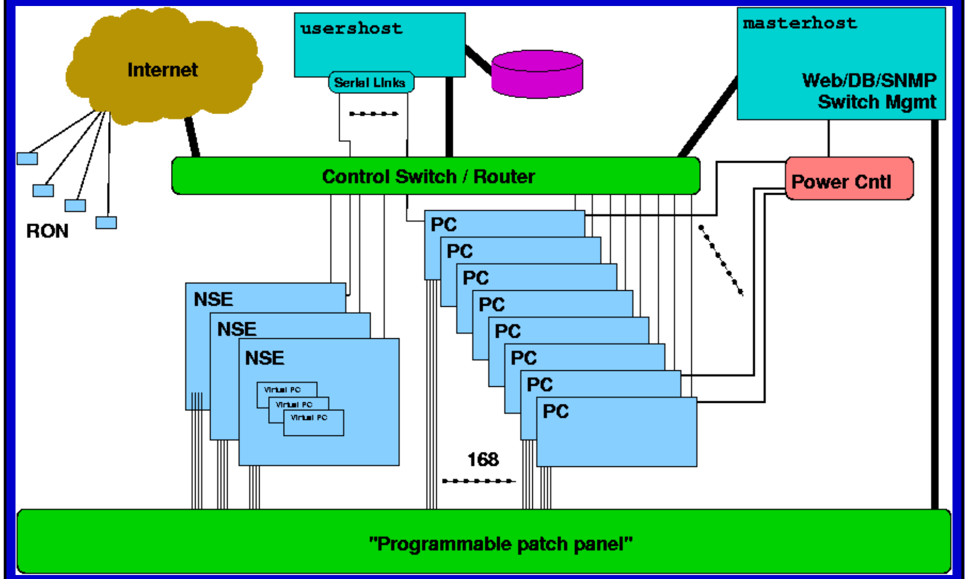
- Allow you to specify that a set of nodes should be of the same type, chosen from a set of possible types
- Make an equivalence class (virtual type)
- Set nodes to be that virtual type
  - Instead of a physical type
- Two kinds of virtual types
  - Soft – Will allow exceptions if resources are scarce
  - Hard – Swapin will fail if class cannot be satisfied

Virtual Types – In Your NS File

- `tb-make-soft-vtype vtype {types}`
- `tb-make-hard-vtype vtype {types}`
- `tb-set-hardware $node vtype`
- **Currently, types can be**
  - **pc600**
  - **pc850**
  - **Any widearea types**

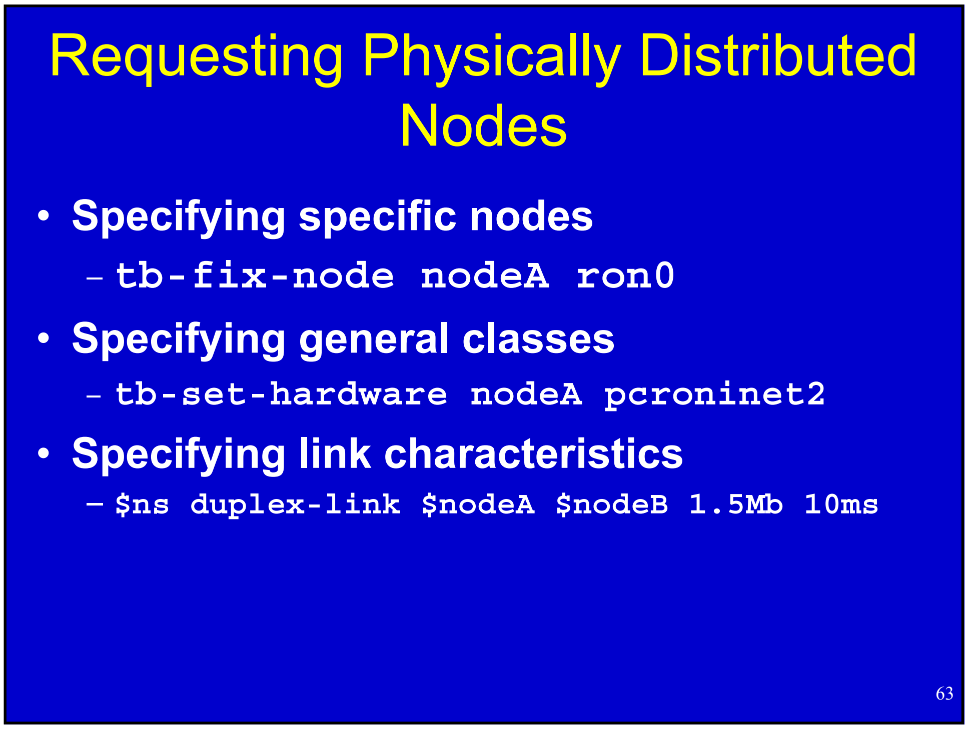
Physically Distributed Nodes

- **Netbed provides access to distributed nodes**
  - Machines from MIT's "RON testbed" (32 as of this writing)
    - Includes Internet2, DSL, and international sites
    - Access policy is more restricted
  - PlanetLab machines
    - Support is evolving
- **Supported features**
  - Account management, ssh key management
  - Optional tunnelling (virtual links)
  - Traffic generation
  - SFS secure distributed filesys



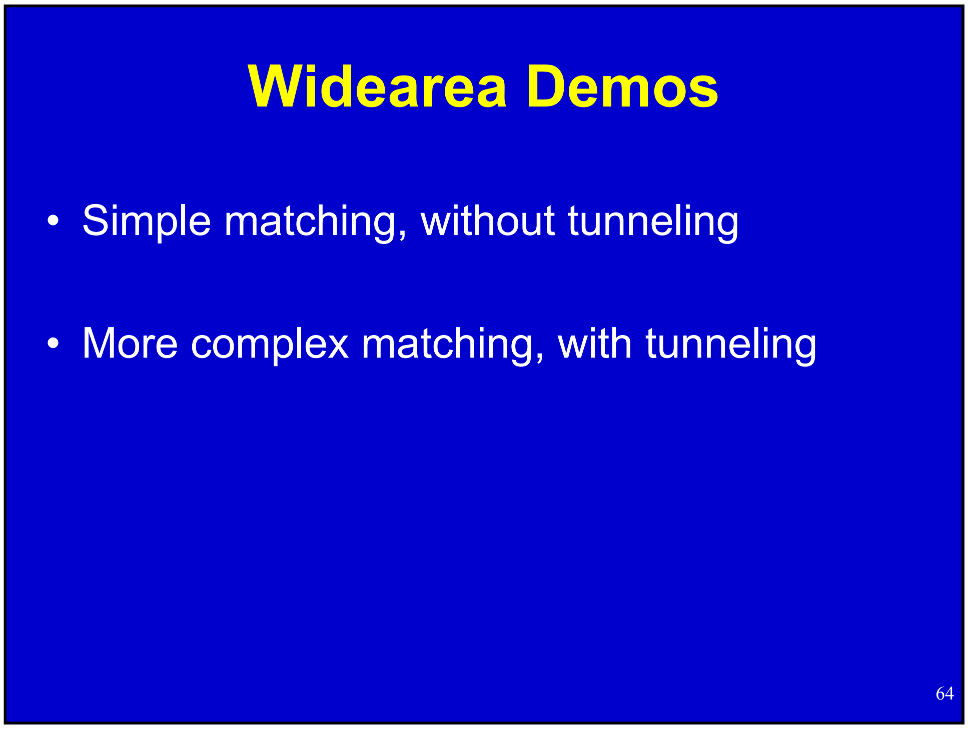
Wide Area Resources

- An experimenter can request
  - N random nodes
  - N specific nodes
  - N, M, …. nodes of certain “last-mile” types: `pcinet2, pcintl, pcdsl, pcinet`
  - As above, but just a piece of a physical node: a “virtual node”
  - N nodes, and M links between them with particular characteristics (can specify any of latency, bw, loss rate).
- In all these cases, Netbed finds the best matching nodes/links from its DB, updated frequently from MIT’s realtime data.



Requesting Physically Distributed Nodes

- **Specifying specific nodes**
  - `tb-fix-node nodeA ron0`
- **Specifying general classes**
  - `tb-set-hardware nodeA pcroninet2`
- **Specifying link characteristics**
  - `$ns duplex-link $nodeA $nodeB 1.5Mb 10ms`



Widearea Demos

- Simple matching, without tunneling
- More complex matching, with tunneling

Using Purely Simulated Nodes

- NSE – The NS emulation facility
- Allows NS to interact with real network
- Packets inside NSE can be converted into real packets and sent on the network
- Packets on the network can be converted into NSE packets, travel through the simulated network, and then return to the real network

Using Simulated Nodes (contd.)

- How to specify simulated nodes in your NS file
- Create an NSE node (physical machine running NSE):
  - `set nsenode [$ns nsenode]`
- Make objects in the simulated world:

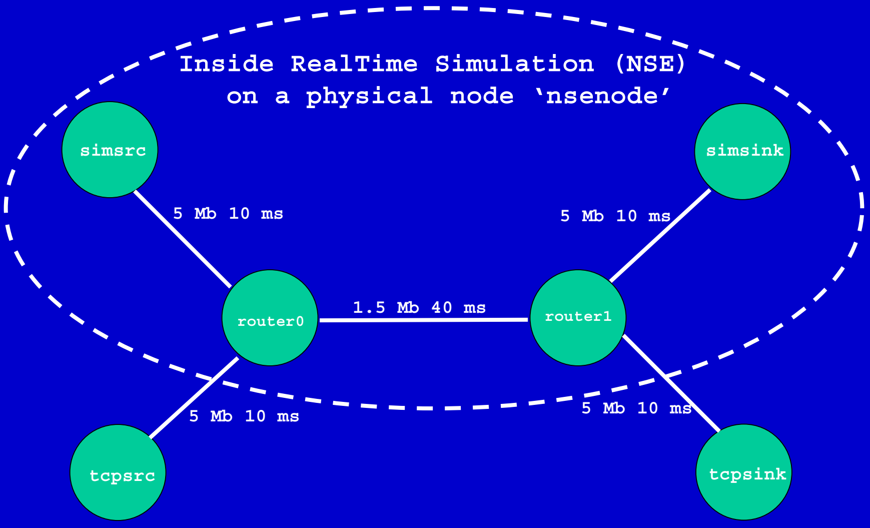
```
– $nsenode make-simulated { # Simulated node
      set simnode [$ns node]
  }
```

- Anything inside `make-simulated` is processed by NSE on `$nsenode`

Using Simulated Nodes (contd.)

- Connections between live/simulated networks are configured automatically (needs to be specified outside `make-simulated` block)

Simulation Integration Demo



Simulation Integration Demo – NS File

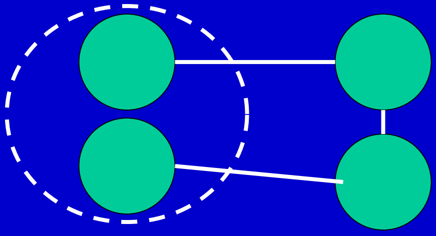
```
set ns [new Simulator]
source tb_compat.tcl
$ns rtproto Static

# Hybrid dumbell topology
set tcpsrc [$ns node]
set tcpsink [$ns node]
set nsenode [$ns nsenode]
$nsenode make-simulated {
        set router0 [$ns node]
        set router1 [$ns node]
        $ns duplex-link $router0 $router1 1.5Mb 40ms DropTail

        set simsrc [$ns node]
        $ns duplex-link $simsrc $router0 5Mb 10ms DropTail
        set simsink [$ns node]
        $ns duplex-link $simsink $router1 5Mb 10ms DropTail
}
$ns duplex-link $tcpsrc $router0 5Mb 10ms DropTail
$ns duplex-link $tcpsink $router1 5Mb 10ms DropTail
$ns run
```

NSE Caveats

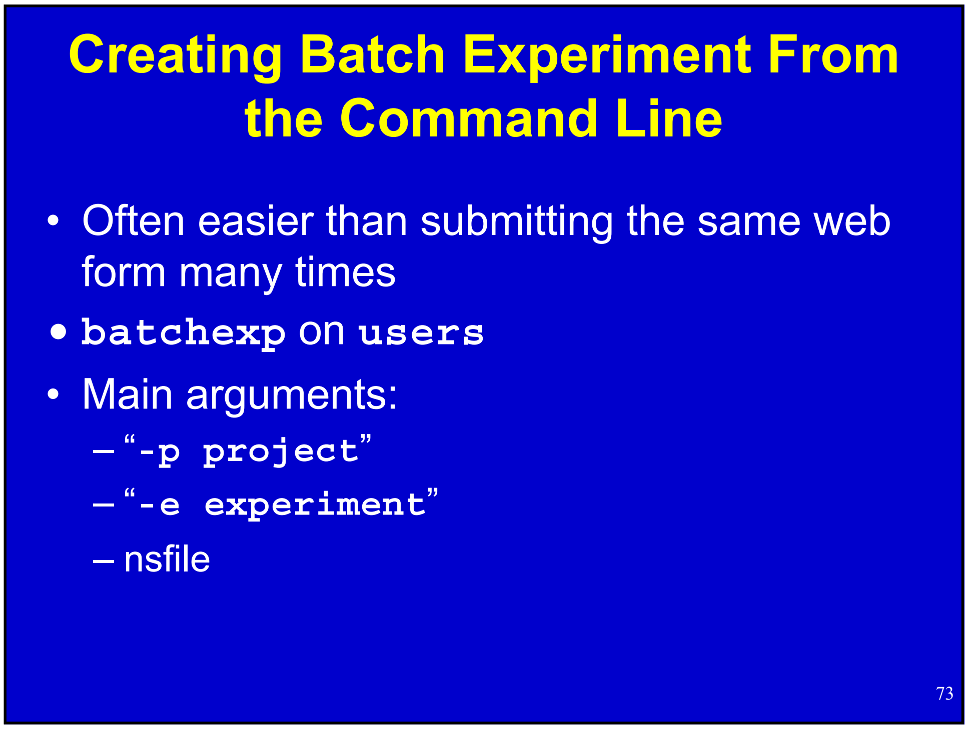
- Our support is still young
- Can have trouble keeping up with too much traffic or too many simulated nodes
- Multiple paths between NSE node and real nodes can be problematic



Simulation Integration Demo

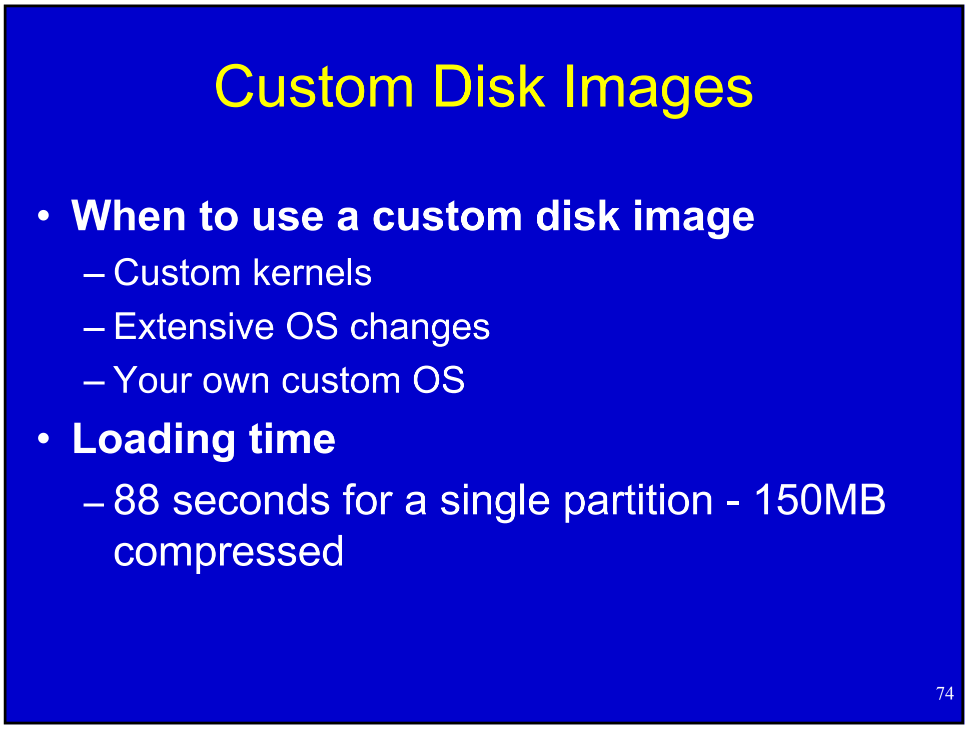
Batch Experiments

- **Batch queue**
- **Runs whenever enough nodes become available**
- **When startup command finishes, experiment is automatically terminated**
- **Great for:**
  - Fitting in large experiments
  - Exploring many topologies/parameters
  - Having work done for you while you sleep!



Creating Batch Experiment From the Command Line

- Often easier than submitting the same web form many times
- `batchexp` on `users`
- Main arguments:
  - "`-p project`"
  - "`-e experiment`"
  - nsfile



Custom Disk Images

- **When to use a custom disk image**
  - Custom kernels
  - Extensive OS changes
  - Your own custom OS
- **Loading time**
  - 88 seconds for a single partition - 150MB compressed

Using a Custom Disk Image

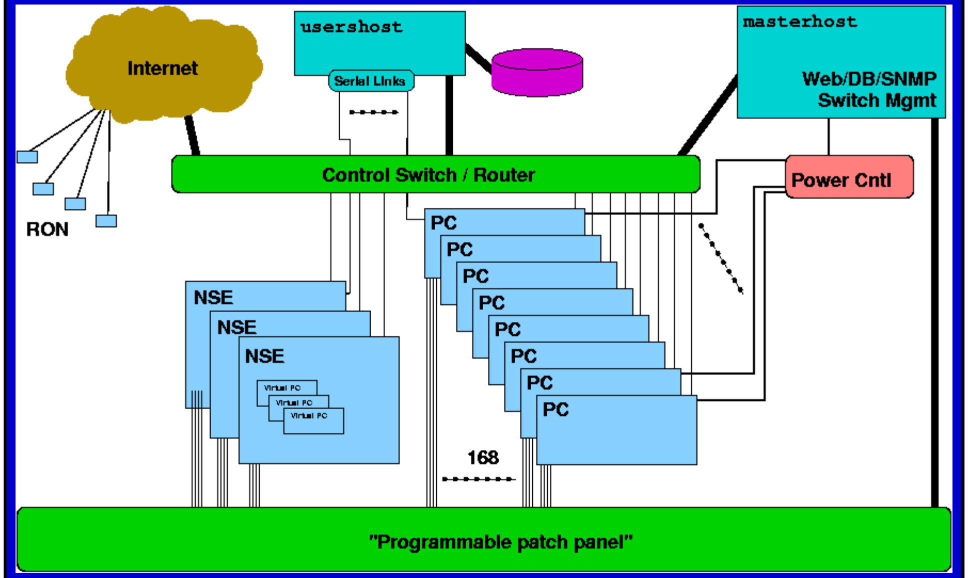
- **Creating - web form**
  - Small web form to fill out ('OSIDs and ImageIDs') link
  - Image gets created automatically
  - [Demo]
- **Specifying in NS file**
  - Automatically loaded for you
  - `tb-set-node-os nodeA FBSD45-MINE`

Debugging Experiments

- **Some common error messages**
  - "Failed to map to reality"
    - Typically: not enough free nodes
    - Recommended approach:
      - Verify against "# of free PCs"
      - Make request less specific (pcxxx -> pc)
      - Try again later
      - Use batch system
  - "pcXXX appears to be dead"
- **Where to find log files**
  - /proj/<proj>/exp/<expt>/log/…

Recovering From Disasters

- Can always do a good old reboot
  - First, we try a graceful reboot
  - Then, we try our custom 'ping of death' (ipod)
  - If all else fails, power cycle
- If the network is down
  - Get in on the serial console
- If all else fails
  - Reload the disk (`os_load` on `users`)



Control vs. Experimental Nets – Differing Purposes

- Control
  - NFS (homedir), DNS, node monitoring
  - Routable to outside world (you log in via it)
  - Not completely isolated today
- Experimental
  - Isolated – no interference from other experiments
  - Configured in the topology you requested
  - 'Clean' – no stray traffic

Control vs. Experimental Nets – How To Tell Them Apart

- IP addresses
  - Control net has 'real' IPs
  - Experimental net has 192.168.*.* or 10.*.*.*
- /etc/testbed/control_interface
  - Prints name (ie. 'eth0' or 'fxp4') to stdout
- If you were expecting delays, bandwidth limits, etc., but don't get them, you may be using the control net by accident

Control vs. Experimental Nets - Naming

- Outside of the nodes
  - Only control net is nameable/reachable
- On the nodes
  - Unqualified names (eg. `nodeA`) refer to directly-connected experimental interfaces
  - Can refer to any experimental interface as '`<node>-<link>`' (`nodeA-link0`, `nodeB-clientLAN`)
  - Qualified names (eg. `nodeA.myexp.myproj`) refer to control net

Barrier-like Synchronization

- Simple barrier synchronization provided by tmcd: the "ready count"
- Nodes can report ready
- Poll for how many other nodes, out of the total number, are ready
  - Make sure to delay a few seconds
- Simple text-based protocol; simple scripting interface

Under the Hood

Netbed Servers

- **Hardware: Netbed Servers**
- **boss.emulab.net**
  - Secure server, no direct access for users
  - Hosts the web server and database
  - Controls everything
- **{users,fs,ops}.emulab.net**
  - Accounts and home dirs for everyone
  - NFS server for boss, nodes
  - Access to node consoles

Software and Experiments

- **Software base:**
  - Web site is PHP, Database is MySQL, NS parser is TCL, back end is mostly perl and C
- **Four main steps to running an experiment**
  - Pre-run: parse NS file, store in DB
  - Swap-in: map expt. to phys. nodes, set up state in DB, reboot nodes, configure nodes
  - Swap-out: Clean up nodes, release them
  - End: Clean out data for experiment
- **Experiment may swap in/out many times**

Selected Hard Problems

- **Resource mapping**
  - NP-hard problem (simulated annealing)
  - Minimize inter-switch bandwidth
  - Make efficient use of node features
- **Experiment swap-in**
  - Automate many system administration tasks
  - Must deal with hardware failures at any time
  - Many automatic conveniences for ease-of-use
- **Disk reloading**
  - Multicast disk loader: Frisbee (think "flying disks")
  - Loads 50 nodes simultaneously in 100 seconds

Node Boot Process

- **Obtains IP through DHCP**
- **NIC boots custom PXE program**
- **Queries boss for which OS to boot**
  - Can boot from disk or network
- **Boots into selected OS**
- **Contacts tmcd for configuration**
  - Accounts, IPs, software to install, delay configuration, traffic generation, etc.

How Has Netbed Been Used?

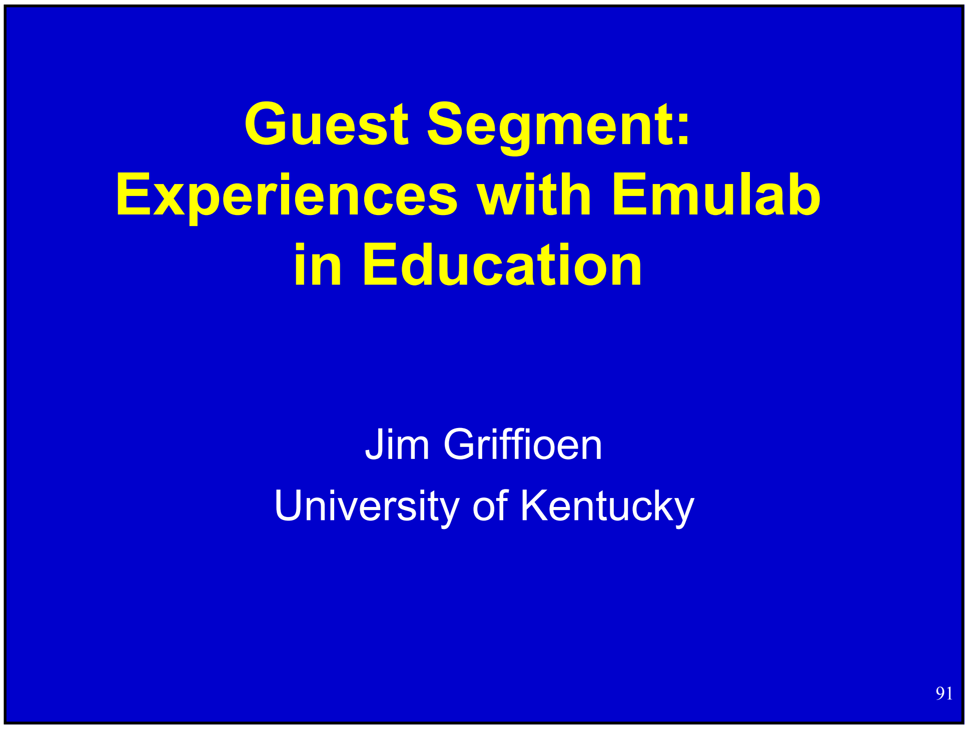
- **Armada (Dartmouth)**
  - Parameter-space exploration
  - Hundreds of batch experiments
- **WanSpread (Johns Hopkins)**
  - Emulated the CAIRN testbed
  - Tried variations with delays doubled and halved
- **SANDS (TASC)**
  - Large topologies, custom disk images
- **Spinglass (Cornell)**
  - Fault tolerant group communication

What Is It Not Good For?

- Packet-level expts. across many nodes
  - Clock synchronization good, but not perfect
  - Non-determinism in the real world
- Experiments that require real routers
  - All nodes are PCs
    - But, we can use a few different queuing strategies
    - And, you can reprogram them all you want
- Experiments that require gigabit links
  - None yet, but we hope to add some
- Experiments that need 1000s of links/nodes
  - ModelNet, coming soon, will help

Netbed In Education

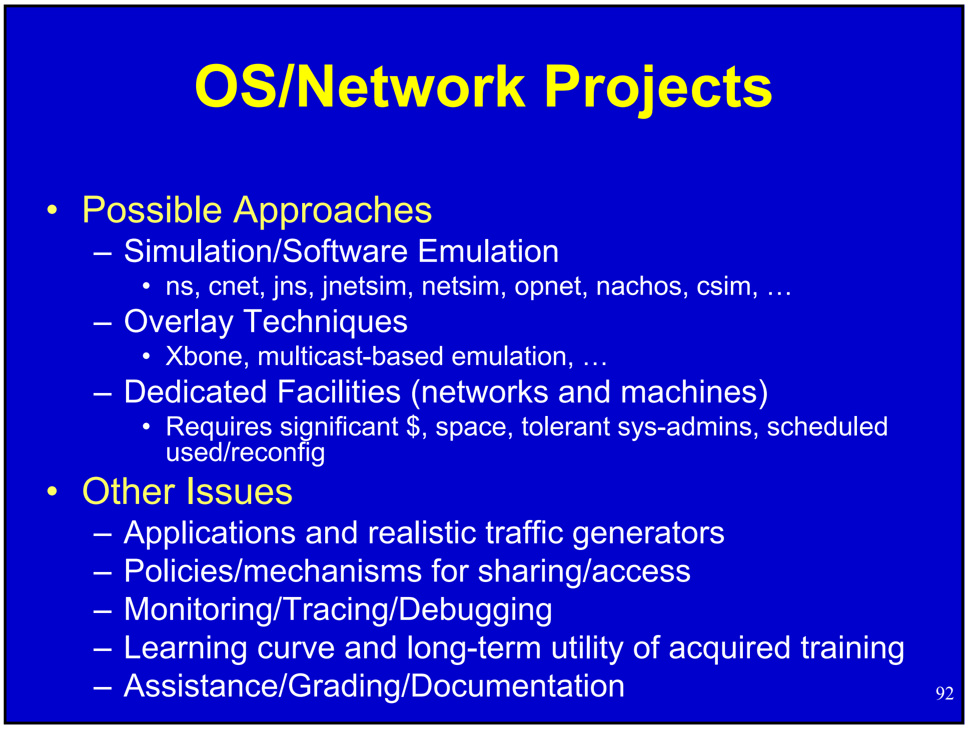
- **Has been used by classes at remote institutions**
  - MIT (Balakrishnan, Andersen)
  - Kentucky (Griffioen)
  - Harvey Mudd (Kuenning)
- **Group model, to give TAs control over student experiments**
- **Safe to give students root access**
- **In OS classes, students can replace kernels, etc.**
- **For networking classes, students can run on an emulated network**



Guest Segment: Experiences with Emulab in Education

Jim Griffioen

University of Kentucky



OS/Network Projects

- Possible Approaches
  - Simulation/Software Emulation
    - ns, cnet, jns, jnetsim, netsim, opnet, nachos, csim, …
  - Overlay Techniques
    - Xbone, multicast-based emulation, …
  - Dedicated Facilities (networks and machines)
    - Requires significant $, space, tolerant sys-admins, scheduled used/reconfig
- Other Issues
  - Applications and realistic traffic generators
  - Policies/mechanisms for sharing/access
  - Monitoring/Tracing/Debugging
  - Learning curve and long-term utility of acquired training
  - Assistance/Grading/Documentation

Why Emulab?

- shared resource – don't have to have your own dedicated facility ($$$)
- sharing policies/mechanism already developed
- no sys admin (or wars with sys admins)
- arbitrary topologies
- reasonable learning curve
- well-known environments, real traffic, real applications
- real protocols
- good supplemental texts exist (i.e., good documentation)
- students will directly use the experience gained
- instructor access
- Standard debugging, tracing, traffic analyzer tools
- Language independence
- OS independence

Types of Projects

- What layers can students work at?
  - User-level applications and services (easy)
  - OS modifications
    - Module-based approach (relatively easy)
    - Modifying built-in components (can probably find a better way)
- Types of projects
  - Routing (ok but can mess up access to the machine)
  - Distributed systems/services (work well)
  - Dynamic network characteristic (doable but take effort)
  - Apps that require special I/O like audio, cameras, etc (have done but suggest avoiding these)
  - Apps that run over X (worked fine for us – YMMV)

Suggestions

- Simplify the learning curve
  - Provide preconfigured scripts, routing, etc as much as possible – students rarely have sys admin experience
  - Time spent teaching the Unix administration steps required by the project will be well spent (e.g., modifying the routing table)
  - Students are easily confused about things like home directory vs /proj directory, what is lost when swapping an experiment, node names and their scope, programs to run on users/ops, reboot vs power cycle, use of sudo, the importance of the control net interface, group access and sharing
  - TCL vs GUI (which is best depends on the student's background and ability)
- Emphasize responsible usage
  - Students forget they are tying up real ($$) machines
  - Comparing topologies is nice, but limit number and size of topologies
- Demonstrate debugging/tracing tools
  - Today's students are clueless
- Think about grading up front
  - Interactive grading sessions
  - Tarball with batch experiments
  - Students code for a well-defined emulab grading environment
- Don't forget the local environment
  - Necessary for code development and initial testing
  - Show students how to sync local environment with emulab

Questions and Feedback

- **Audience questions**
- **What features would make Netbed more useful?**
  - **Most of our features are driven by user demand**

Contributing to the Distributed Netbed

- **What we provide**
  - CD-ROM, maybe a disk sometimes
  - Working OS installation
  - Database state
- **What you provide**
  - Machine
  - Switch port
  - IP address
- **Caveats**
  - Security may be a concern
  - May consume bandwidth occasionally

Building Your Own

- **Our software is portable to other sites**
  - Kentucky has built their own
  - Georgia Tech is working on another
- **Lots of tradeoffs between price and usability**
  - Degree of nodes
  - Level of control (serial consoles, power control)
  - Big switches vs. stacks of small switches
  - Rack mount vs. desktop cases
- **Hardware recommendations on our website**

Ongoing and Future Work

- **Integrating Duke's "ModelNet"**
- Wide area, PlanetLab
- Federation
  - heterogeneous sites
  - resource allocation
- Wireless nodes, mobile nodes
- Hierarchical nodes (multiplex, VM)
- Pre-emptive swapout, rollback, "single-step"
- IXP1200 nodes, tools, code fragments
  - Routers, high-capacity shapers
- Scheduling system
- Packet capture, logging, visualization tools
- Microsoft OSs, high speed links, more nodes…

Conclusions

- Easy to use, while giving experimenters lots of control
- Suitable for distributed systems, network, and OS research and education
- Powerful NS/Tcl input language
- Integrates emulation, simulation, and wide-area experimentation
- Sign up for a project at www.netbed.org!

Afternoon Tutorial

- **Get a laptop with wireless support (alone or pair up)**
- **It will need to provide:**
  - Internet access
  - Web browser (Netscape/IE/Opera are tested)
  - SSH client
  - An editor (preferred but optional)
- **We provide pre-built accounts on Utah Netbed**

Available for universities, labs, and companies, for research and teaching, at:

www.netbed.org
www.emulab.net

Afternoon: The Lab Session

Using Your Guest Account

- Log in at www.emulab.net
- Optional: "Update User Information"
  - Change password
    - cracklib in use, good passwords only
  - Add ssh public key (link at bottom of page)
- Receive mail on users.emulab.net
  - Read mail directly
  - (or) Make a .forward file to send to another account

Using Your Guest Account (cont'd)

- Log into `users.emulab.net` via ssh
  - Hostname reported as '`ops`'
  - Keep at least one shell on this machine open
- Make sure you can read mail
  - There should be one message already in your inbox
- Make sure you have an editor you're comfortable with
  - Either on `users,` or on your laptop

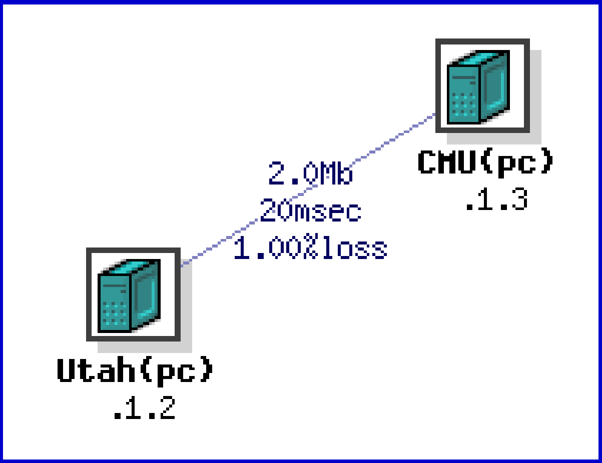
Experiments Overview

- Three experiments
  - First, get something simple going with our GUI
  - Next, make something a little more complex by editing NS files directly
  - Finally, use some advanced features to make a moderately complex experiment
  - Each one will build on the last
- We have a few example/template files on `users` in `/proj/tutorial/ns/`

Starting an Experiment – NS Files

- Edit on your local machine
  - Use file upload box on experiment creation form
- Or, edit on `users`
  - Place file in your home dir or `/proj/tutorial/`
  - Your home directory is `/users/<username>/`
  - Put **full** path to NS file in form's textbox
- To get NS file from netbuild
  - Choose "Create Experiment"
  - Click "View NS File"

Experiment 1 Topology



Experiment 1

- Make two nodes (`Utah` and `CMU`)
  - Use NetBuild if your browser supports Java
- Link them together – name the link link0
  - Bandwidth 2Mb
  - 20ms one-way latency
  - 1% packet loss

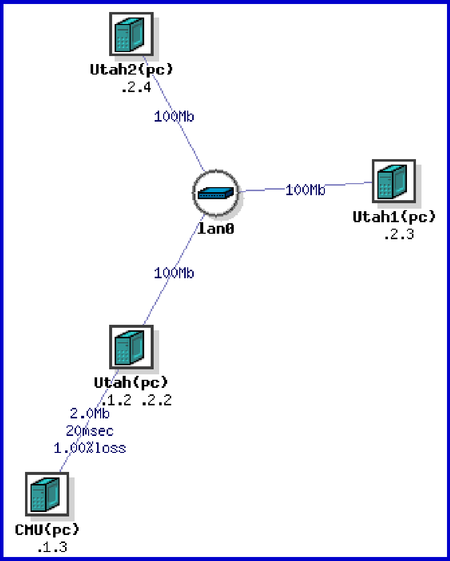
Experiment 1 (cont'd)

- "Begin Experiment" when ready
  - Two things to enter:
    - Name, description
    - Pick any name, just make sure it's one no one else is likely to pick
  - Wait for experiment creation mail
    - Watch realtime experiment creation log
- Explore experiment page on web interface
  - Use "More Detail" link in visualization to verify parameters

Experiment 1 (cont'd)

- Log into **`Utah`**
  - Ping on control and experimental interfaces
    - **`CMU`** (test network)
    - **`CMU.<expt>.tutorial`** (control network)
- Swap experiment out
- Swap experiment back in
- Terminate experiment

Experiment 2 Topology



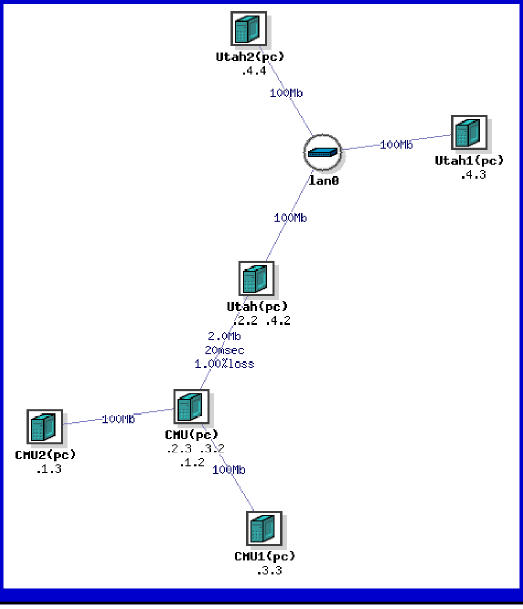
Experiment 2

- Start with NS file from Experiment 1
- Add two new nodes (`Utah1` and `Utah2`)
- Make a LAN called `lan0` containing `Utah`, `Utah1`, and `Utah2`
  - 100 Mb, no latency or packet loss
- Install some software on `Utah`
  - `/proj/tutorial/rpms/trafshow.rpm`
- Set startup command for `Utah1`
  - `/proj/tutorial/bin/simplescript`
- Enable static routing

Experiment 2 (cont'd)

- Begin experiment
- Log into `Utah` and run `trafshow`
- Log into `CMU` and ping `Utah1-lan0` to confirm routing setup
- Log into `users.emulab.net`
  - Use '`console`' to view a node's serial console
  - Use '`node_reboot`' or webpage to reboot it
- Terminate experiment

Experiment 3 Topology



Experiment 3

- Start with the NS file from Experiment 2
- Add two more nodes (`CMU1` and `CMU2`)
  - Connect them directly to `CMU` (full bandwidth, no delay)
- Set up two constants to set OSes
  - `RHL-STD` for routers
  - `FBSD-STD` for end nodes
  - Set `Utah` and `CMU` to the router OS, and the other to the end node OS

Experiment 3 (cont'd)

- Create two traffic generators
  - One, sending TCP at 100Mb from **`CMU1`** to **`Utah1`** (call the application **`cbr0`**)
  - The other, sending UDP at 100Mb from **`CMU2`** to **`Utah2`** (call the application **`cbr1`**)
- Turn the first traffic on and off at 10 second intervals
- Leave the second traffic off

Experiment 3 (cont'd)

- Have **`Utah1`** prepare to run a program with a program object called **`prog0`**
  - **`/proj/tutorial/bin/simpledaemon`**
- Begin the experiment
- Log into an end node and check the OS
- Log into **`Utah`**
  - Find its interface to **`CMU`**
    - (Hint: Use **`ifconfig`** and experiment creation mail)
  - Run **`trafshow`** on that interface to watch TCP traffic go on and off

Experiment 3 (cont'd)

- Log into `users`
  - Start UDP cross traffic
    - `tevc -e tutorial/<expt> now cbr1 start`
  - Watch the TCP stream get clobbered with `trafshow`
  - Start and stop the program object
    - `tevc -e tutorial/<expt> now prog0 start`
    - Logs these events to `/tmp/simpledaemon.log`
- Terminate Experiment

Expt Creation Scaling

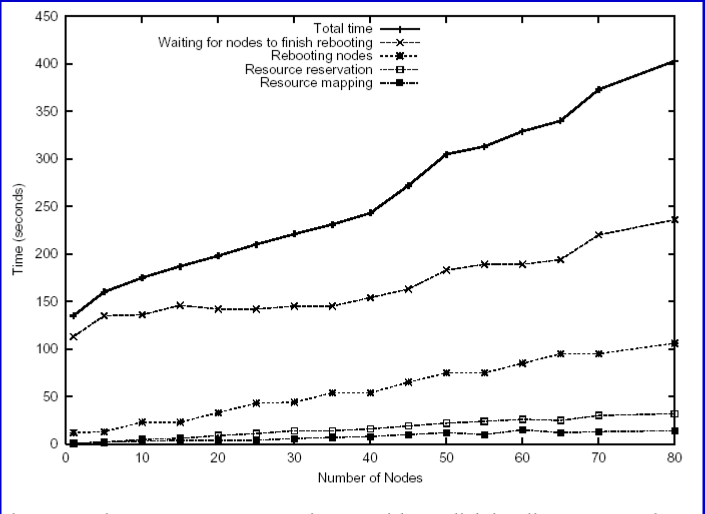


Figure 4: Time to create an experiment without disk loading. Stages shown

Join the federation!
Or just use it.

Where network fantasies become reality:

www.netbed.org

Bonus Slides

Who Uses Netbed?

- **Researchers**
  - Distributed systems
  - Networking (traditional and “active”)
  - Operating systems
- **Educators**
  - Advanced networking class at MIT
  - Basic networking class at Univ. Kentucky
  - OS class at Harvey Mudd College
  - Student projects
- **Advanced developers**
- [Browse project list on www.netbed.org]

Other Experimental Environments

- Simulation
  - Fast prototyping, easy to use, easy to control, but less realistic
- Live networks
  - Realistic, but hard to control, measure, or reproduce results
- Small static testbeds *emulating* a network
  - Real hardware and software, but hard to configure and maintain, lack scale

All 3 live on, implying both the continued importance and inadequacies of each

Key Points

- Netbed seamlessly *integrates* all three: simulation, emulation, and live networks
- Netbed's primary goals: *ease of use, control,* and *realism*. Unlike the constituent approaches, meets all 3 goals simultaneously
  - Can mix and match in same experiment

- Netbed brings orders of magnitude improvements to the *emulation approach:* our focus today
- This all works *today,* and most is in full production mode for external users

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Primary Design Principles

- Transparency
  – Common specification language: *ns*
  – Common namespaces for nodes, links, agents…
- Virtualization
  – of all IP addrs, hosts, hostnames, links, …
  – Level of indirection allows
    - Control and configuration
    - Efficient time sharing (swapping to different physical resources)
    - Scalability via seamless multiplexing

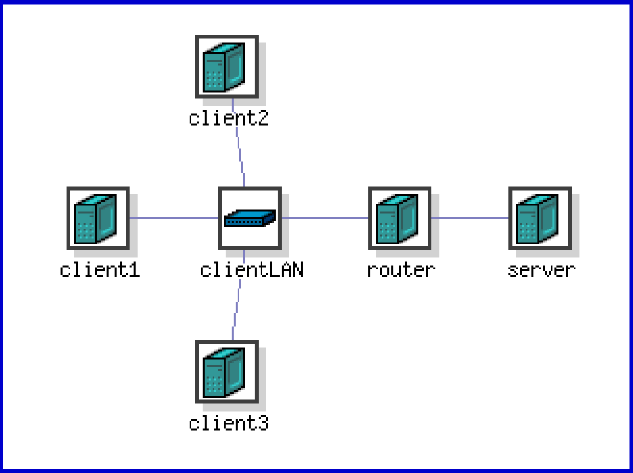
Design Principles (cont'd)

- Automation
  - Replaces hundreds of steps of manual configuration
  - Arbitrary programmatic control through integrated event system and general-purpose PL for spec (Tcl)
- Efficiency
  - Of use of physical resources (space and time-shared)
  - Of experimenters' time: interactive style of use
- Policy today: conservative resource allocation

Simple NS file

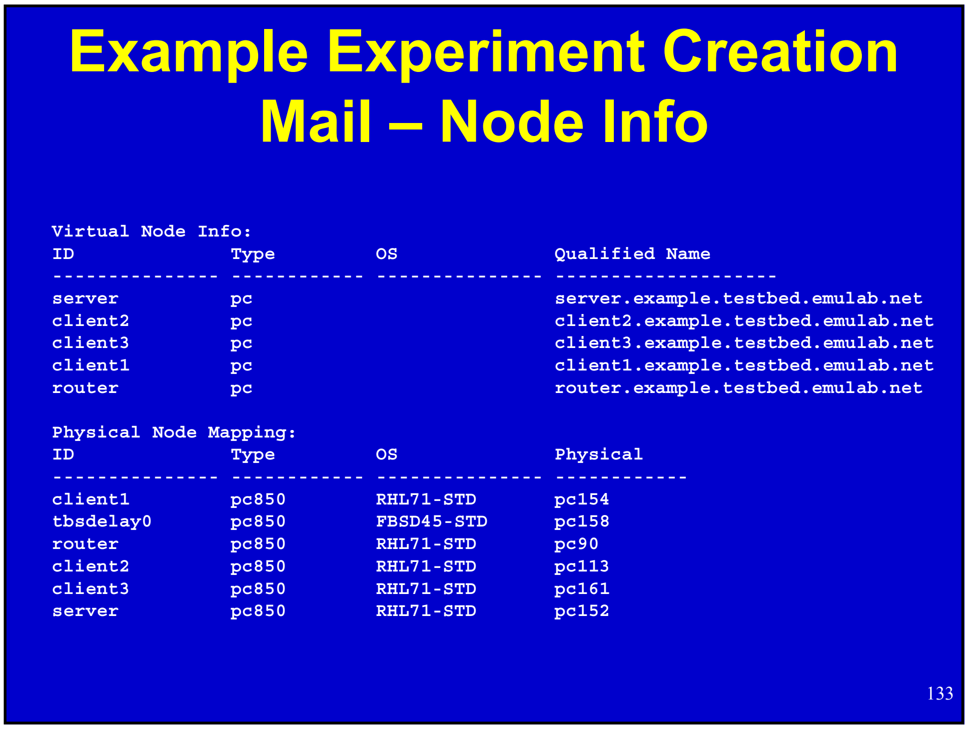
```
set $ns [new Simulator]
source tb-compat.tcl

set nodeA [$ns node]
set nodeB [$ns node]

$ns duplex-link $nodeA $nodeB 100Mb 0ms DropTail

$ns run

# Comments look like this
```

Example Experiment Creation Mail – Topology



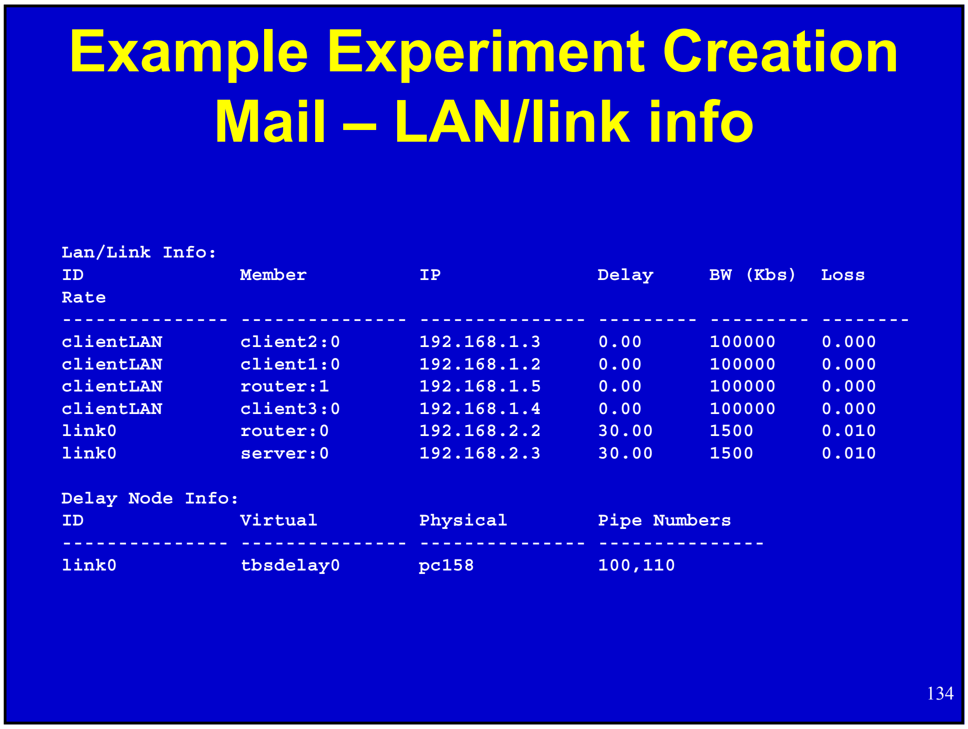
Example Experiment Creation Mail - Overview

```
User:          Robert P Ricci
EID:           example
PID:           testbed
GID:           testbed
Name:          An example experiment
Created:       2002-07-31 16:14:05
Expires:       2002-11-28 00:00:00
Started:       2002-07-31 16:19:18
Directory:     /proj/testbed/exp/example
```



Example Experiment Creation Mail – Node Info

```
Virtual Node Info:
ID              Type         OS              Qualified Name
--------------- ------------ --------------- --------------------
server          pc                           server.example.testbed.emulab.net
client2         pc                           client2.example.testbed.emulab.net
client3         pc                           client3.example.testbed.emulab.net
client1         pc                           client1.example.testbed.emulab.net
router          pc                           router.example.testbed.emulab.net

Physical Node Mapping:
ID              Type         OS              Physical
--------------- ------------ --------------- ------------
client1         pc850        RHL71-STD       pc154
tbsdelay0       pc850        FBSD45-STD      pc158
router          pc850        RHL71-STD       pc90
client2         pc850        RHL71-STD       pc113
client3         pc850        RHL71-STD       pc161
server          pc850        RHL71-STD       pc152
```



Example Experiment Creation Mail – LAN/link info

```
Lan/Link Info:
ID              Member          IP              Delay     BW (Kbs)  Loss
Rate
--------------- --------------- --------------- --------- --------- --------
clientLAN       client2:0       192.168.1.3     0.00      100000    0.000
clientLAN       client1:0       192.168.1.2     0.00      100000    0.000
clientLAN       router:1        192.168.1.5     0.00      100000    0.000
clientLAN       client3:0       192.168.1.4     0.00      100000    0.000
link0           router:0        192.168.2.2     30.00     1500      0.010
link0           server:0        192.168.2.3     30.00     1500      0.010

Delay Node Info:
ID              Virtual         Physical        Pipe Numbers
--------------- --------------- --------------- ---------------
link0           tbsdelay0       pc158           100,110
```