SMT Solvers For Configuration And Some Configuration Projects

Lecture 5

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References For Lectures 2-5

- Use of Prolog for configuration file analysis, specification, validation, verification and configuration
  - Network Configuration Validation. Sanjai Narain, Gary Levin, Rajesh Talpade. Chapter in Guide to Reliable Internet Services and Applications, edited by Chuck Kalmanek (AT&T), Richard Yang (Yale) and Sudip Misra (IIT). Springer Verlag, 2010
  - Using Service Grammar to Diagnose Configuration Errors in BGP-4. Proceedings of USENIX Large Installation System Administration (LISA) Conference , San Diego, CA, 2003.

- ConfigAssure: Solutions to configuration problems and use of Kodkod/SAT
  - Declarative Infrastructure Configuration Synthesis and Debugging. S. Narain, V. Kaul, G. Levin, S. Malik. Journal of Network Systems and Management, Special Issue on Security Configuration, eds. Ehab Al-Shaer, Charles Kalmanek, Felix Wu. 2008.

- Testbed based on description in
  - Building Autonomic Systems via Configuration. Proceedings of AMS Autonomic Computing Workshop, Seattle, WA, 2003.

The Story So Far

- Discussed how Prolog can be used:
  - To analyze ad hoc configuration language files
  - To evaluate whether requirements are true of configurations
  - As a metalevel language to convert to other forms such as Graphviz dot files

- Motivated the need for constraint solvers for firewall verification
  - Used Prolog as a metalevel language to generate constraints and exploit the power of modern constraint solvers

- Discussed the use of constraint solvers for configuration problems:
  - Synthesis
  - Diagnosis
  - Repair
  - Repair at minimum cost
  - Reconfiguration planning (later)

Today

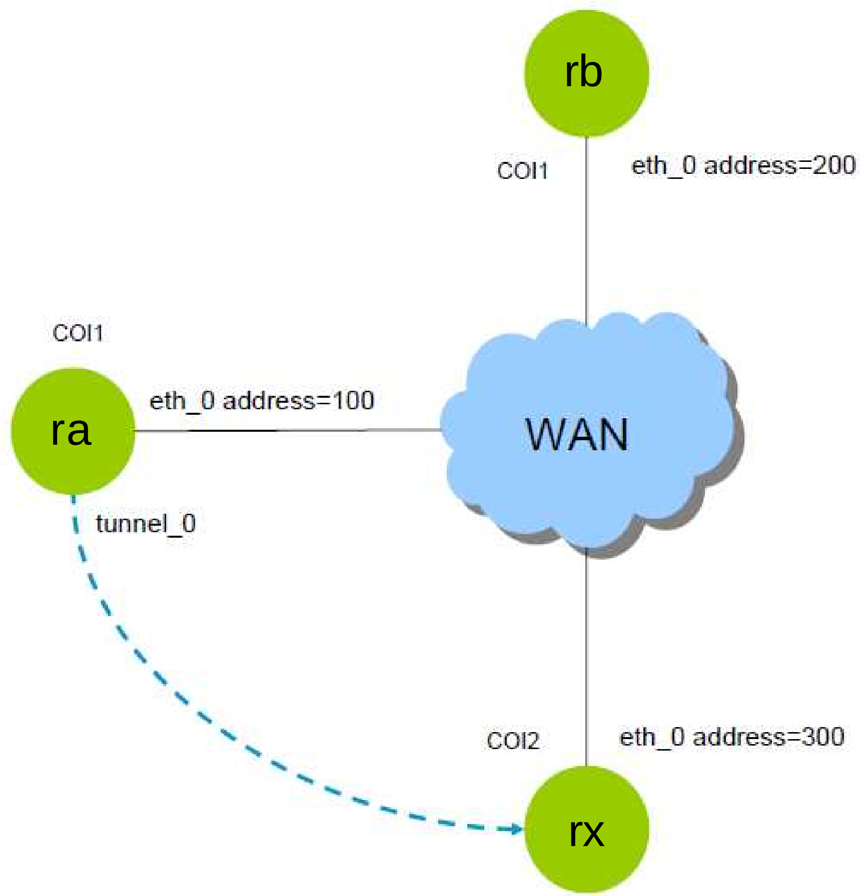
- Show how to build in partial evaluation into the definition of eval to improve solution efficiency
- Discuss the problem of naming large numbers of configuration variables
- Motivate the use of SMT solvers for EUF to solve it
- Discuss configuration-related projects

Partial Evaluation In eval Predicate

- eval(Req, QFF) transforms a requirement into an equivalent QFF
- Before submitting the QFF to Kodkod, evaluate parts of it to drastically reduce size of Kodkod/SAT problem
- Even better: don't even generate true or false parts of a QFF
- Example:
  - If there are N distinct addresses, and new host has to be added
  - Then, there are N*(N+1)/2 constraints to specify that all addresses are distinct
  - However, only N constraints are needed to ensure that host address is distinct from existing ones
- This logic can be built into eval

Variable Naming Problem: QFFs Reference Configuration Variables

```
?- eval(and(good, not(bad)), C)
     C= and[
              gre_a_local=ra_addr
              gre_a_remote=rb_addr
              dest=rb_addr
              not [
                or[
                  and[
                    gre_a_local=ra_addr
                    gre_a_remote=rx_addr
                  ]
                  dest=rx_addr
                ]
              ]
            ]
```



Configuration database with variables

gre(ra, tunnel_0, **gre_a_local**, **gre_a_remote**).
ipAddress(ra, eth_0, **ra_addr**, 0).
ipAddress(rb, eth_0, **rb_addr**, 0).
ipAddress(rx, eth_0, **rx_addr**, 0).
static_route(ra, **dest**, **mask**, 400).

But, How To Name Large Numbers of Variables?

It is hard to give a distinct name to each variable, and remember it when constructing the QFF

Solution: use function applications. Construct large number of variables by combining a small number of function symbols

gre_a_local	local_gre(ra, tunnel_0)
gre_a_remote	remote_gre(ra, tunnel_0)
ra_addr	ip_address(ra, eth_0)
rb_addr	ip_address(rb, eth_0)
rx_addr	ip_address(rx, eth_0)
	next_hop(ra, ip_address(rx, eth_0), 32)

Now rewrite eval rules:

```
eval(gre_tunnel(RX, RY), and(
                              remote_gre(RX, tunnel_0) = ip_address(RY, eth_0),
                              local_gre(RX, tunnel_0) = ip_address(RX, eth_0))
    ).
eval(route_available(X, Y), not(next_hop(X, ip_address(Y, eth_0), 32)=0)).
```

The Equality With Uninterpreted Functions Language

- Fortunately, SMT solvers for the Equality with Uninterpreted Function symbols can take constraints with variables as function applications, and efficiently reason with these.

- The EUF language is as follows from "Exploiting Positive Equality in a Logic of Equality with Uninterpreted Functions" by R. Bryant, S. German, M. Velev http://www.cs.cmu.edu/~bryant/pubdir/cav99a.pdf

$$
\begin{aligned}
\mathit{term} &::= \mathit{ITE}(\mathit{formula}, \mathit{term}, \mathit{term}) \\
&\quad \mid \mathit{function\text{-}symbol}(\mathit{term}, \ldots, \mathit{term}) \\
\mathit{formula} &::= \mathbf{true} \mid \mathbf{false} \mid (\mathit{term} = \mathit{term}) \\
&\quad \mid (\mathit{formula} \wedge \mathit{formula}) \mid (\mathit{formula} \vee \mathit{formula}) \mid \neg \mathit{formula} \\
&\quad \mid \mathit{predicate\text{-}symbol}(\mathit{term}, \ldots, \mathit{term})
\end{aligned}
$$

- ITE is the if-then-else operator.

- Good SMT solvers are Yices, CVC3 and OpenSMT. They also contain bitshift operators that can be used for network addressing.

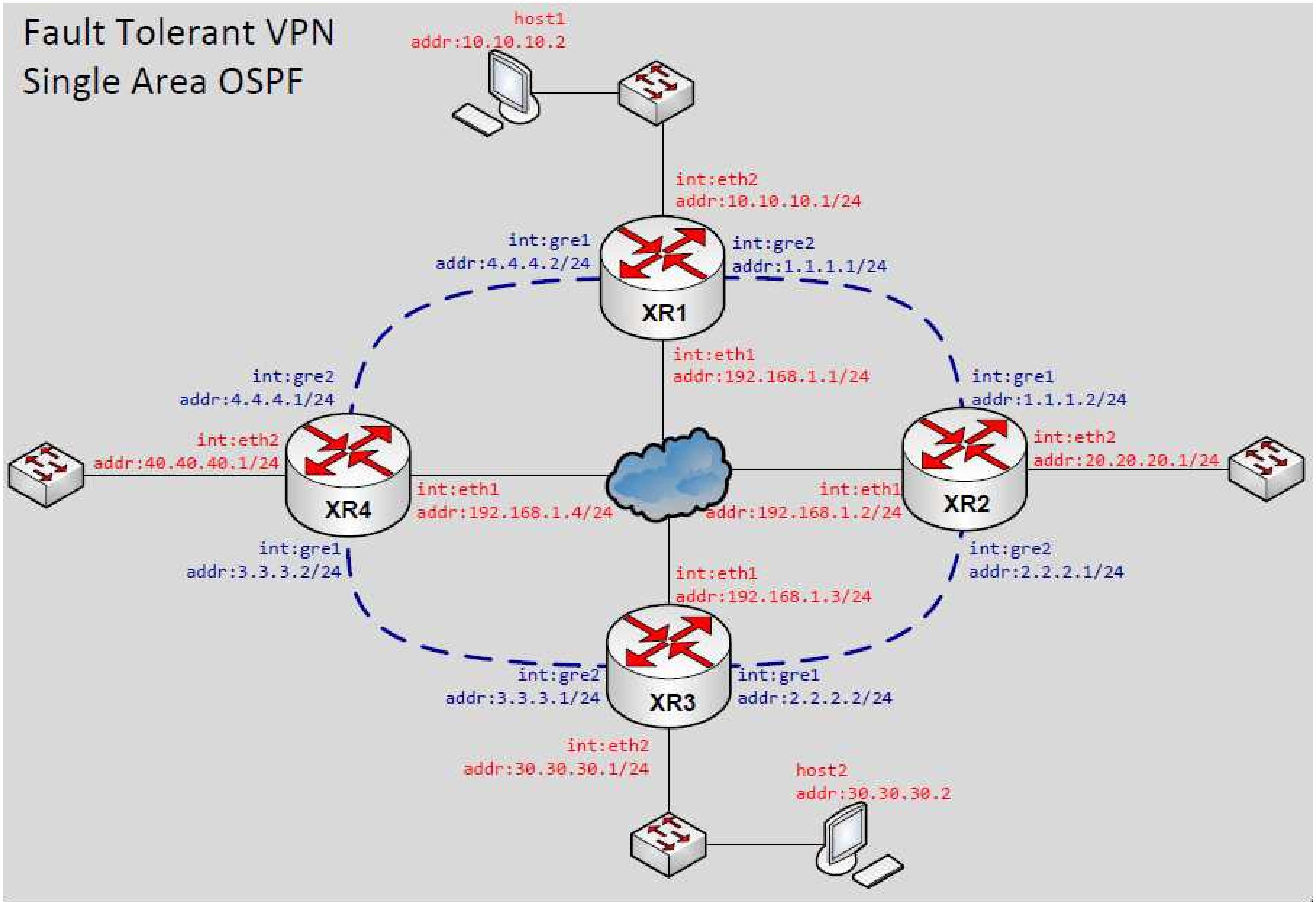
New Constraint And Its Solution With SMT Solver For EUF

```
?- eval(and(good, not(bad)), C)

C=
and[
  remote_gre(ra, tunnel0)=ip_address(rb, eth0)
  local_gre(ra, tunnel0)=ip_address(ra, eth0)
  not [
    next_hop(ra, ip_address(rb, eth0), 32)=0
  ]
  not [
    or[
      and[
        remote_gre(ra, tunnel0)=ip_address(rx, eth0)
        local_gre(ra, tunnel0)=ip_address(ra, eth0)
      ]
      not [
        next_hop(ra, ip_address(rx, eth0), 32)=0
      ]
    ]
  ]
]
```

Solver produces

```
ip_address(ra, eth0)=34
local_gre(ra, tunnel0)=34
ip_address(rb, eth0)=33
remote_gre(ra, tunnel0)=33
next_hop(ra, 33, 32)=35

ip_address(rx, eth0)=36
next_hop(ra, 36, 32)=0
```

Configuration Projects Testbed

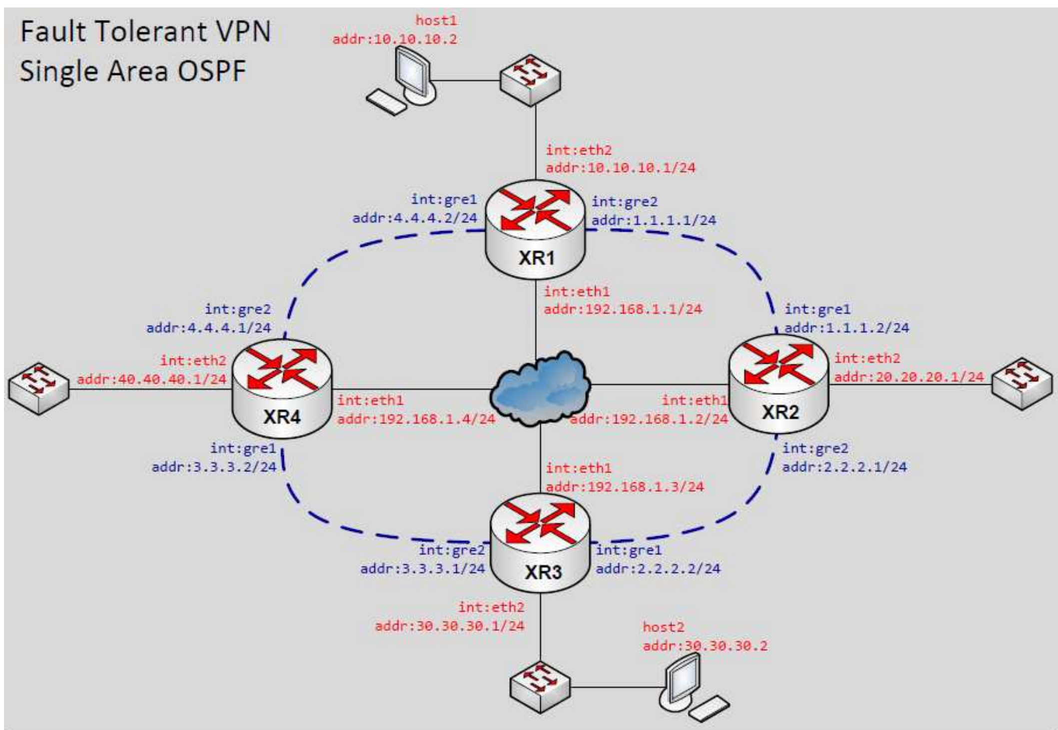


VPN Implemented With Current Practice

Administrator Creates 12 files like this

```
interfaces {
   restore-original-config-on-shutdown: true
   interface gre1 {
      description: "Tunnel to XR1"
      disable: false
      default-system-config
   }
   interface gre2 {
      description: "Tunnel to XR3"
      disable: false
      default-system-config
   }
   interface eth2 {
      description: "Local Hosts"
      disable: false
      default-system-config
   }

}
```

New VPN Implementation Practice



Synthesis system will generate configurations and then all the files

Administrator creates specification like this

% Host-side router interfaces

subnet([xr1-eth2])

subnet([xr2-eth2]).

subnet([xr3-eth2]).

subnet([xr4-eth3]).

% GRE tunnels

subnet([xr1-gre1, xr4-gre2]).

subnet([xr4-gre1, xr3-gre2]).

subnet([xr3-gre1, xr2-gre2]).

subnet([xr2-gre1, xr1-gre2]).

% OSPF domain

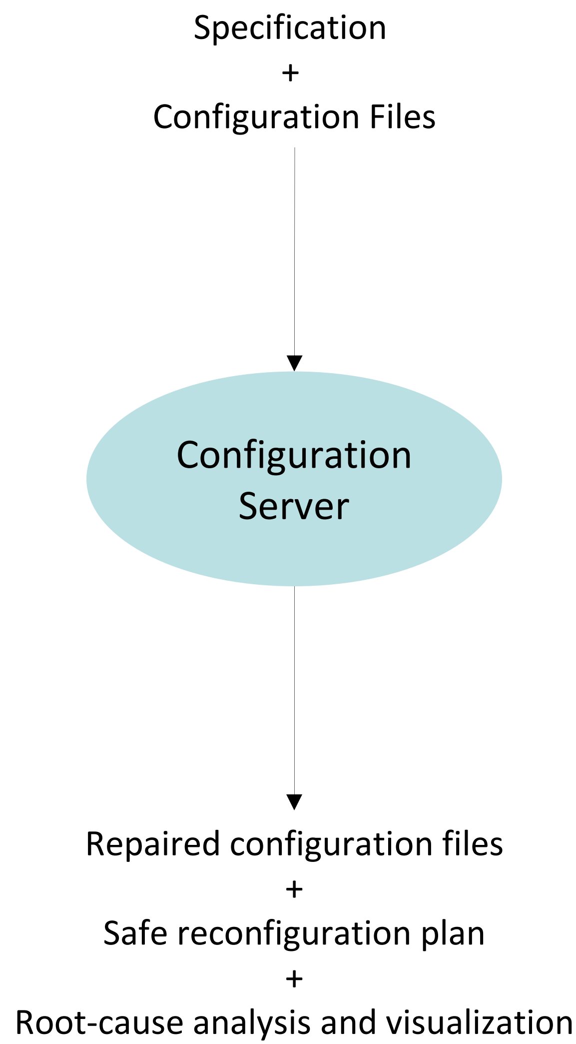
ospf([xr1-gre1, xr4-gre2, xr4-gre1, xr3-gre2, xr3-gre1,
xr2-gre2, xr2-gre1, xr1-gre2, xr1-eth2, xr2-eth2,
xr3-eth2, xr4-eth2]).

% Static routing

next_hop(host1, 0.0.0.0, 32)=ip_address(xr1-eth2).

next_hop(host2, 0.0.0.0, 32)=ip_address(xr3-eth2).

A Web-Based Configuration Service



Towards A Requirement/Constraint Library

- Create a set of useful constraints
- Allow a user to compose these with logical operators to define complex constraints
- Classes of constraints
  - Integrity of logical structures associated with protocols
  - Connectivity
  - Security
  - Reliability
  - Performance
  - Best practices

Requirement Library For Fault-Tolerant VPN

Configuration variables are of the form

- ip_address(H, I)
- mask(H, I)
- local_gre(H, I)
- remote_gre(H, I)
- next_hop(H, Dest, Mask)
- ospf_area(H, I)
- ospf_hello_interval(H, I)
- ospf_dead_interval(H, I)

Primitive constraints are of the form

configuration variable=value

Complex constraints

gre_tunnel(G_1, T_1, G_2, T_2) $\rightarrow$

remote_gre(G_1, T_1)=local_gre(G_2, T_2), and

local_gre(G_1, T_1)=remote_gre(G_2, T_2)

local_gre(G, T) is an address on G

subnet([H_1-I_1,..,H_k-I_k]) $\rightarrow$

$\forall$i. ip_address(H_i, T_i) <u>bitwiseand</u> mask(H_i, T_i) is same

ospf_subnet([H1-I1,..,Hk-Ik]) $\rightarrow$

$\forall$i. ospf_area(H_i, I_i) is same, and

$\forall$i. ospf_hello_interval(H_i, I_i) is same, and

$\forall$i. ospf_dead_interval(H_i, I_i) is same

All IP addresses are distinct

All IP addresses are in a given range

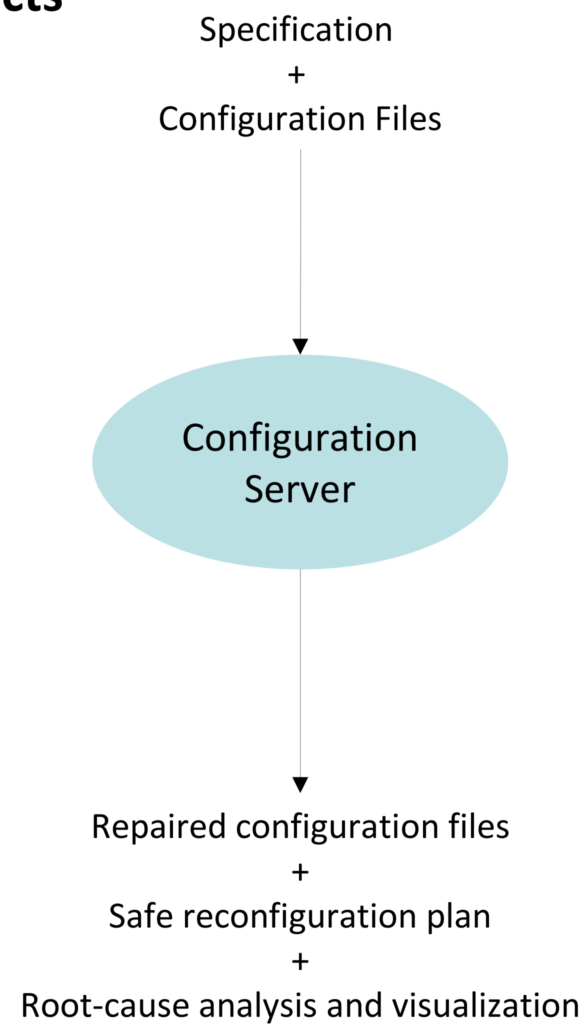
Configuration-Related Projects

- Prolog: Implement
  - Configuration file analyzer
  - Configuration file builder
  - Configuration visualizer
  - Configuration validator

  Evaluate against testbed

- SMT solver: Implement ConfigAssure's
  - Synthesis algorithm
  - Minimum-cost repair algorithm
  - Reconfiguration planning algorithm

  Evaluate against testbed



Jointly Build This For Fault-Tolerant VPN

Next Class: The Use of Alloy For Configuration

- The challenges that arose and the resolution that led to ConfigAssure
- Will also be preparation for Pamela Zave’s lectures on Alloy for verification