Network Configuration Management: Theory and Practice of Routing Correctness Testing

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Why Network Management?

- network management is necessary
  - design from scratch is expensive, rare
  - networks need to be managed and evolved
    - for most of their lifecycle
    - with iterative methodologies [Oppenheimer04, Teare07]
Why Network Management?

- network management is necessary, and **crucial**
  - large businesses **lose 3.6%** (on avg.) of annual revenue due to network downtime [infonetics04]
  - downtime **costs several millions of USD/h** for critical apps [YankeeGroup04]
  - **almost 80%** of IT budget is reserved to network management [YankeeGroup04]
How Hard Can it Be?
How Hard Can it Be?

- heterogeneous devices
  - in type and vendors
How Hard Can it Be?

- lots of heterogeneous devices
  - > 1000 routers in the biggest networks
How Hard Can it Be?

- low-level device configuration
- few automation
How Hard Can it Be?

- distributed protocols
  - that interact among them
How Hard Can it Be?

- strict end-to-end requirements
  - connectivity
  - availability
  - performance
  - security
  - ...

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Some Problems - By Analogies

- Consistency and predictability in a **distributed system**
- Functionality allocation boils down to be an **optimization** problem
- **Security** requirements are fundamental
- Configuration management is similar to **software** management
  - configurations can be thought is the software component of networks
Some Problems - By Analogies

- Consistency and predictability in a distributed system
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- Configuration management is similar to software management
  - configurations can be thought is the software component of networks
  - with focus on routing
(IP) Routing in the Internet
(IP) Routing in the Internet

Internet Service Provider (ISP)
(IP) Routing in the Internet

- (e)BGP selects the ISP path
  - basically, a path on a big graph
Isn’t It Simple ?

- BGP is **policy-based**
  - no shortest-path anymore
    - not all path information is propagated
    - path preference is locally defined
- policies are **autonomously** set by ISPs
  - no global coordination (by design) \(\rightarrow\) conflicting policies \(\rightarrow\) routing inconsistencies
Theories for BGP

- **Routing algebras** [Griffin05]
  - semi-rings with non-distributive metrics
  - local optima differ from global optimum
- **Game theoretical approaches** [Nisan07]
  - BGP actors are players with different strategies
  - look for Nash equilibrium
- **Graph-based models** [Griffin99]
  - arranged to take into account dynamics
Restricting to a Single ISP

- configuration is under control of the same entity
Still Not Simple?

- IGP+iBGP show the same issues of eBGP [Griffin02]
  - decisions are still taken locally
- Two concurrent reasons
  - partial path visibility
    - scalability → information hiding
  - interaction between BGP and IGP
    - BGP decision is (partially) based on IGP metrics
    - IGP decides the path between two BGP hops
Routing (In)Correctness

- **problem**: routing must be **consistent**
  - convergence to a stable state [Griffin02]
  - every router should have a route to each destination *
  - no forwarding loop [Griffin02]

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  - no forwarding loop \cite{Griffin02}
- avoid never-ending synchronization attempts
  - similarly to distributed systems and database synchronization problems

Routing Configuration Testing

- routing depends on device configurations
- *problem*: how to check router configurations?
  - statically
  - for dynamic routing correctness
  - similarly to software unit testing
- use cases
  - before deployment / changes
  - what-if analyses
The Research Perspective
Modeling BGP Networks

- Graph-based model (SPP [Griffin02])
  - nodes are BGP routers
  - node 0 is the destination
  - links are BGP communication channels (peerings)
Modeling BGP Networks

- A list of **permitted paths** is attached to each node
  - paths that do not appear in a list have been **filtered**
  - the list is ordered according to **local path preference**
Convergence Problems

- In some cases, BGP never converges
  - under specific message timings
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Convergence Problems

- In some cases, BGP never converges
  - under specific message timings
- Even worse, BGP may not be able to converge *for any message timing* !!!
  - no stable state [Griffin99]
Cyclic structure of preferences are the root cause of convergence [Griffin02]

- such a structure is called Dispute Wheel (DW)
- in a DW, each node prefers its clockwise neighbor
- No DW → convergence guarantees

note that DWs are static structures
Did I say “easy”? 

- Spoke and Rim paths can arbitrarily intersect
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Testing for Convergence

HAS A STABLE STATE (NP-hard)

SAFE

SUF

NO DISPUTE RING

NO DISPUTE WHEEL
Testing for Convergence *

HAS A STABLE STATE (NP-hard)

SAFE

SUF

NO DISPUTE REEL

Testing for Convergence **

HAS A STABLE STATE (NP-hard)

SAFE (coNP-hard)

SUF

NO DISPUTE

REEL (coNP-hard)

From Theory to Practice ***

Cittadini et al. “From Theory to Practice: Efficiently Checking BGP Configurations for Guaranteed Convergence”, TNSM 2011
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Testing Takes Subseconds

![Graph showing elapsed time vs. number of iBGP speakers]
Conclusions

- Routing testing is trickier than what it looks like
  - new problems
    - optimality problems in presence of local preferences
  - new theory
    - semirings algebraic structures without distributivity
    - models for asynchronous message exchange and state inconsistencies
  - new algorithms and tools
    - for static checking of dynamic consistency properties
Open Problems

- Theory
  - models for more general routing schemes
  - algorithmic improvements
  - extension to other configuration management tasks
- Practice
  - defeat low-level implementation using abstractions
  - overcome misconfigurations via automation
A Broader View

- Exchanges with other scientific fields are possible
  - networks are distributed systems posing consistency problems
  - security requirements are fundamental
  - optimization techniques are often needed
  - challenging algorithmic problems arise
  - graph theory, algebra, game theory proved to be useful for theoretical studies
Thank You!

- Questions?