Reasoning about Software Defined Networks

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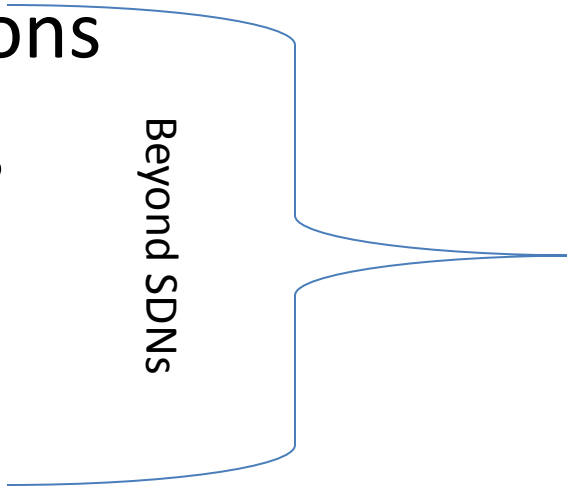
Some slides from J. Rexford POPL'12 invited talk

Some Lessons from Michael's talk

- Some tasks are more suitable for distribution
  - Frequently Executed
  - Simple
  - Regular
  - Can be implemented in hardware
  - Data is distributed
- Some tasks can be executed sequentially without effecting scalablity
  - Complicated
  - Rarely executed
  - Increase the effectiveness of the distributed process
- The SDN provides an interesting compromise
- OpenFlow is a reasonable realization

Content

- Challenges in SDNs
- Programming Language Abstractions
- Programming Language Principles
- Program Language Tools
- Other useful tools



Challenges in SDN

- Programming complexity
- Modularity
- Composing operations
- Handling Updates
- Reliability
- Performance
- Testing
- Productivity
- Non-expert programmers

How hard is it to program networks

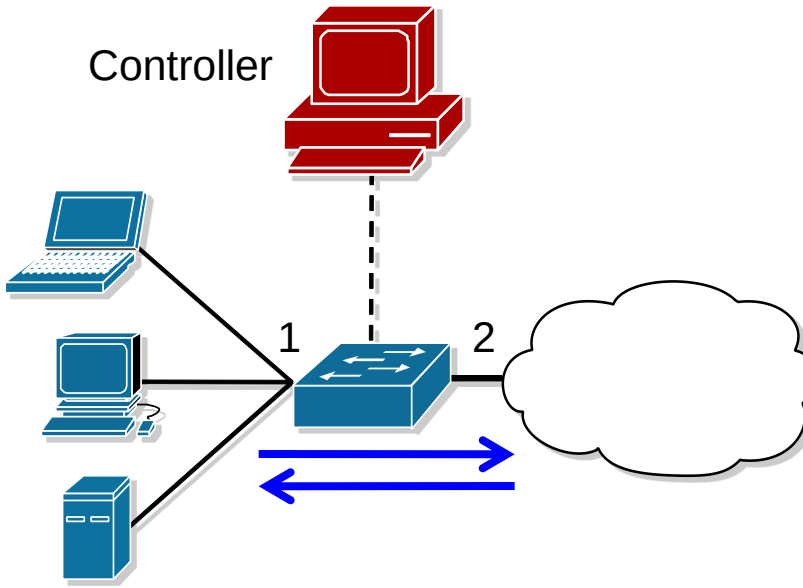
- Routers with 20+ million lines of code
- Cascading failures, vulnerabilities, etc
- Low level programming
- No abstractions
  - Virtual memory
  - Operating Systems
  - Resource Allocations
  - Libraries
  - Types

Modularity: Simple Repeater

Simple Repeater

```
def repeater(switch):
  # Repeat Port 1 to Port 2
  pat1 = {in_port:1}
  act1 = [forward(2)]
  install(switch, pat1, DEFAULT, act1)

  # Repeat Port 2 to Port 1
  pat2 = {in_port:2}
  act2 = [forward(1)]
  install(switch, pat2, DEFAULT, act2)
```



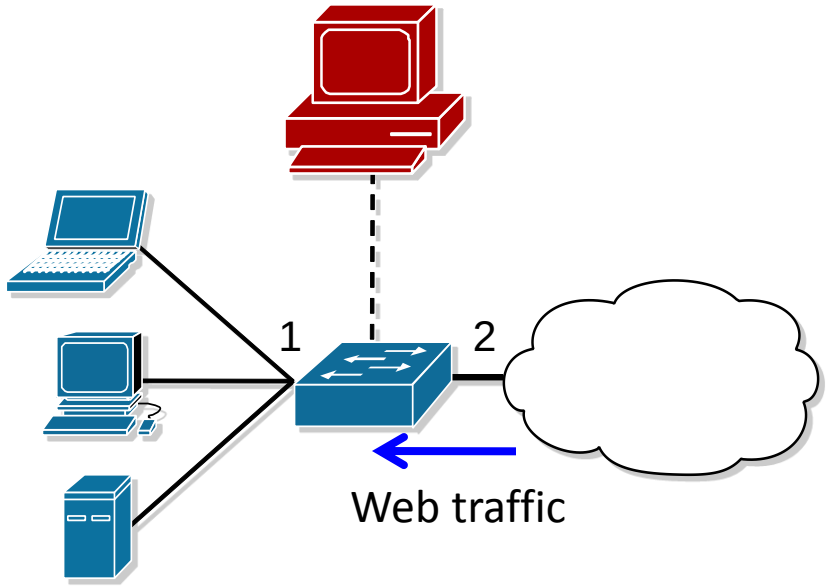
When a switch joins the network, install two forwarding rules.

Composition: Web Traffic Monitor

Monitor Web (“port 80”) traffic

```
def web_monitor(switch)):
  # Web traffic from Internet
  pat = {inport:2,tp_src:80}
  install(switch, pat, DEFAULT, [])
  query_stats(switch, pat)

def stats_in(switch, pat, bytes, …)
  print bytes
  sleep(30)
  query_stats(switch, pat)
```



When a switch joins the network, install one monitoring rule.

Composition: Repeater + Monitor

Repeater + Monitor

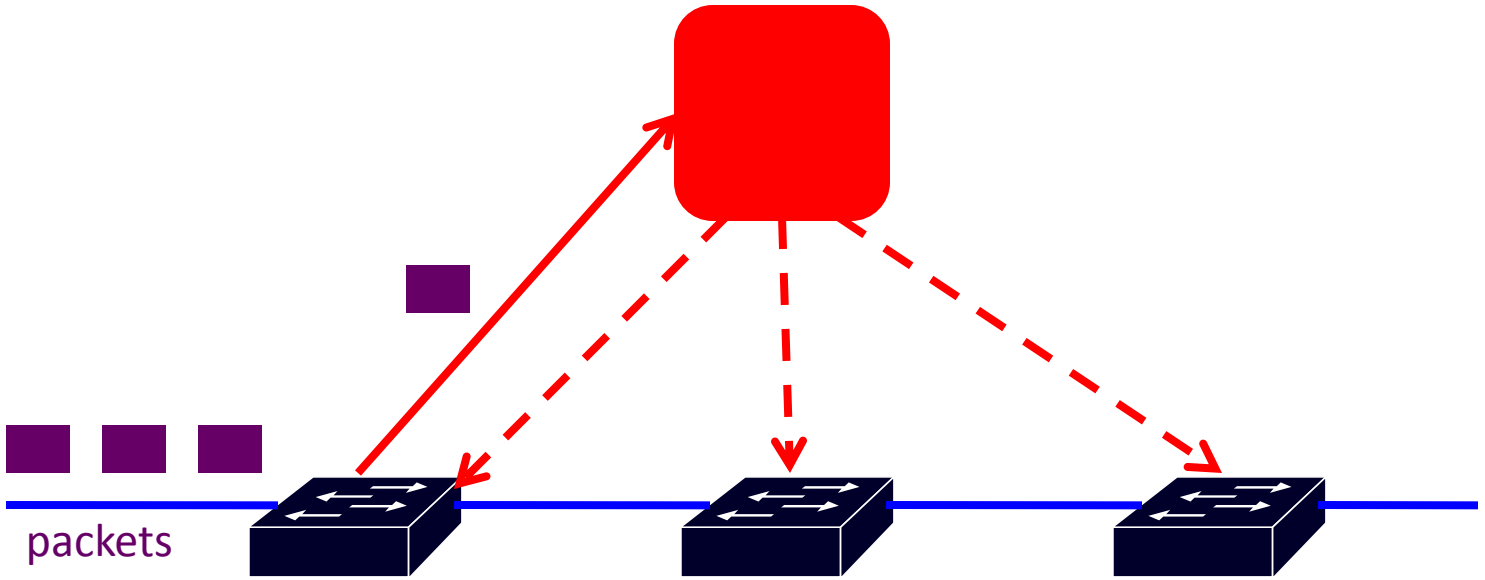
```
def switch_join(switch):
  pat1 = {inport:1}
  pat2 = {inport:2}
  pat2web = {in_port:2, tp_src:80}
  install(switch, pat1, DEFAULT, None, [forward(2)])
  install(switch, pat2web, HIGH, None, [forward(1)])
  install(switch, pat2, DEFAULT, None, [forward(1)])
  query_stats(switch, pat2web)

def stats_in(switch, xid, pattern, packets, bytes):
  print bytes
  sleep(30)
  query_stats(switch, pattern)
```

Must think about both tasks at the same time.

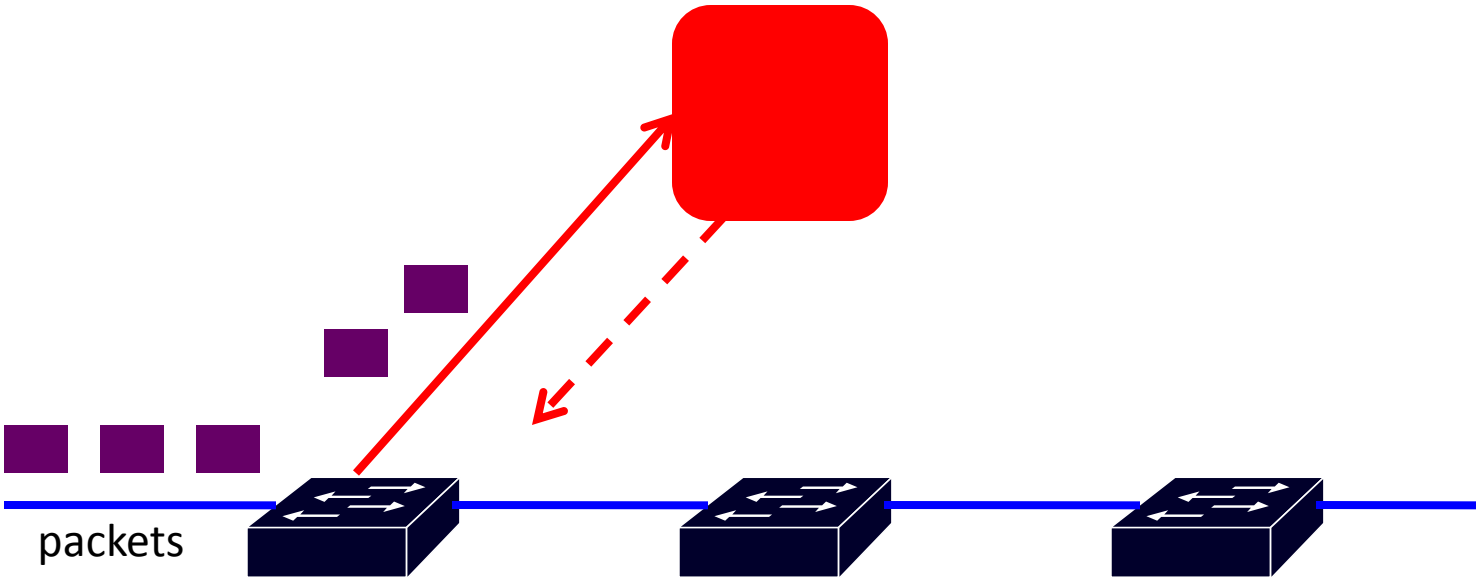
Concurrency: Switch-Controller Delays

- Common programming idiom
  - First packet goes to the controller
  - Controller installs rules



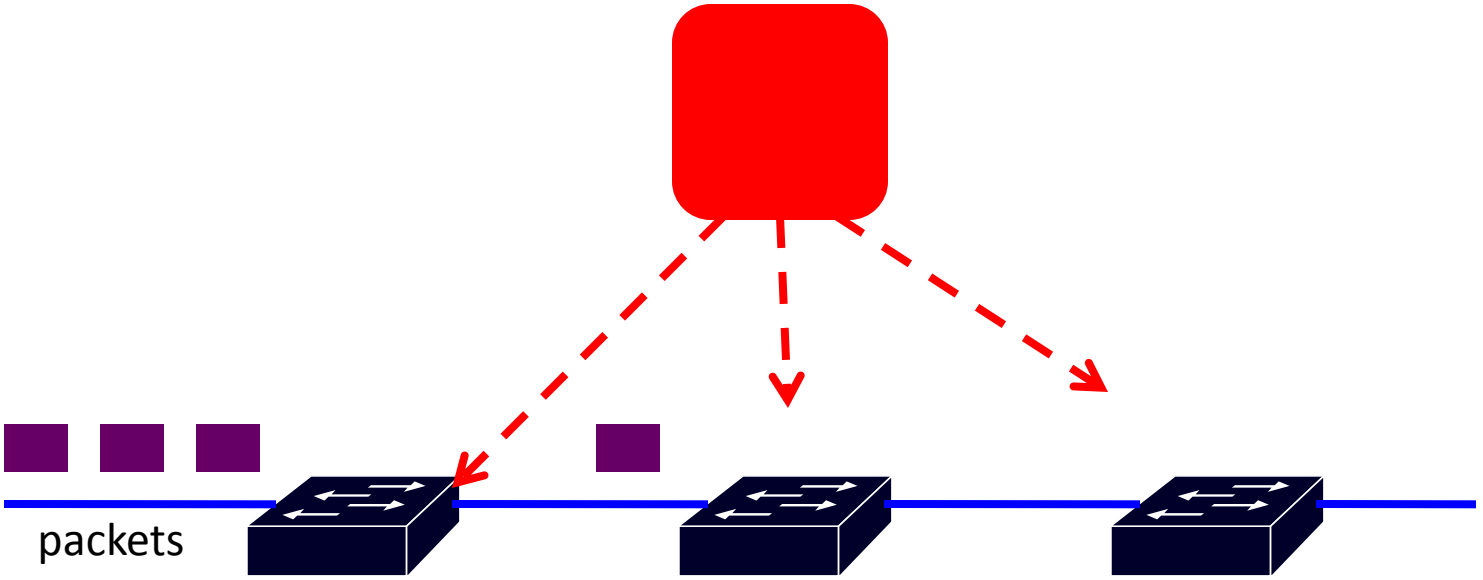
Concurrency: Switch-Controller Delays

- More packets arrive before rules installed?
  - Multiple packets reach the controller



Concurrency: Switch-Controller Delays

- Rules along a path installed out of order?
  - Packets reach a switch before the rules do



Must think about all possible packet and event orderings.

Debugging is hard[*Kazemian* NSDI'13]

- Distributed switch tables
- Varied delays
- Cascading effects on switch tables
- Multiple protocols
- Human interaction
- …

SDN Performance

- Given an SDN controller code
- Estimate the cost of routing per packet
  - Length of the path
  - Weight of the path
  - Number of controller interventions

Programming Language Abstractions

- Hide the implementation
- Interpreter/Compiler guarantees performance
- Benefits
  - Portability
  - Ease of use
  - Reliability
  - Compositionality
  - Productivity

Language Abstractions

- Procedures
- Data Types
  - Enumerated types
  - Arrays
- Abstract data types
- Classes and Objects
- Resources
  - Memory management
  - Garbage collection

- Control abstractions
  - Exceptions
  - Iterators
  - Tree Pattern Matching
  - Higher order functions
  - Continuation
  - Lazy evaluation
  - Monads
- Libraries
- Domain specific languages
- Declarative programming

Programming Language Principles

- Rigorously define the meaning of programs
- Supports abstraction
- Prove compiler correctness
- Prove that two SDN programs are observationally equivalent
  - The same packet transmissions

A Simple Example

- Numeric Expressions
  - <exp> ::= <exp> **+** <exp> | < exp> ***** <exp> | **number**
- The semantic of expressions is a number
  $E[\![]\!]$: <exp> $\rightarrow$ *int*
- Inductively defined
  - $E[\![n]\!] = n$
  - $E[\![e_1 + e_2]\!] = E[\![e_1]\!] + E[\![e_2]\!]$
  - $E[\![e_1 * e_2]\!] = E[\![e_1]\!] * E[\![e_2]\!]$
- Compositional
- Fully abstract
- $e_1 \approx e_2$ iff $E[\![e_1]\!] = E[\![e_2]\!]$
- $5 + 6 \approx 7 + 3 + 1$

A Simple Example + Var

- Numeric Expressions
  - <exp> ::= <exp> **+** <exp> | <exp> ***** <exp> | **number** | **id**
  - <com> ::= **skip** | **id** **:=** exp | <com> **;** <com>
- Need to introduce states
  Var $\rightarrow$ *Int*
- Examples
  - $[x \mapsto 2, y \mapsto 3]\ x =$
  - $[x \mapsto 2, y \mapsto 3]\ z =$
  - $[x \mapsto 2, y \mapsto 3][z \mapsto 5] = [x \mapsto 2, y \mapsto 3, z \mapsto 5]$
  - $[x \mapsto 2, y \mapsto 3][x \mapsto 5] = [x \mapsto 5, y \mapsto 3]$
  - $[x \mapsto 2, y \mapsto 3][x \mapsto 5]x = 5$
  - $[x \mapsto 2, y \mapsto 3][x \mapsto 5]y = 2$

A Simple Example + Var

- Numeric Expressions
  - <exp> ::= <exp> **+** <exp> | <exp> * <exp> | **number** | **id**
- The semantic of expressions is a function from states to numbers
  $E[\![\,]\!]$: <exp> $\rightarrow$ *(Var $\rightarrow$ Int) $\rightarrow$ Int*
- Inductively defined
  - $E[\![n]\!]\sigma = n$
  - $E[\![e_1 \textbf{ + } e_2]\!]\sigma = E[\![e_1]\!]\sigma + E[\![e_2]\!]\sigma$
  - $E[\![e_1 \textbf{ * } e_2]\!]\sigma = E[\![e_1]\!]\sigma * E[\![e_2]\!]\sigma$
  - $E[\![id]\!]\sigma = \sigma$ id
  - $E[\![\textbf{x+2}]\!][x \mapsto 5] = E[\![\textbf{x}]\!]\,[x \mapsto 5] + E[\![\textbf{2}]\!]\,[x \mapsto 5] = [x \mapsto 5]x + 2 = 5 + 2 = 7$
  - $x + x \approx 2 * x$
  - $e1 + e2 \approx e2 + e1$

The semantics of commands

- Commands
  - <com> ::= **skip** | **id** **:=** exp | <com> **;** <com> | **id**
- The semantic of command is a function from states to states
  C⟦⟧: <com> → *(Var → Int) → (Var → Int)*
- Inductively defined
  - $C[\![skip]\!]\sigma = \sigma$
  - $C[\![id := e]\!]\sigma = \sigma[id \mapsto E[\![e]\!]\sigma]$
  - $C[\![c_1 ; c_2]\!]\sigma = C[\![c_2]\!](C[c_1]\sigma)$
  - $c ; skip \approx skip ; c \approx c$
  - $c_1 ; (c_2 ; c_3) \approx (c_1 ; c_2) ; c_3$

Benefits of formal semantics

- Can be done for arbitrary languages
- Automatically generate interpreters
- Rational language design
- Formal proofs of language properties
  - Observational equivalence
  - Type safety
- Correctness of tools
  - Interpreter
  - Compiler
  - Static Analyzer
  - Model Checker

A Simple Controller Language

- No packet changes
- No priorities
- No statistics
- Simple updates
  - Per-flow installation

A Simple Controller Language

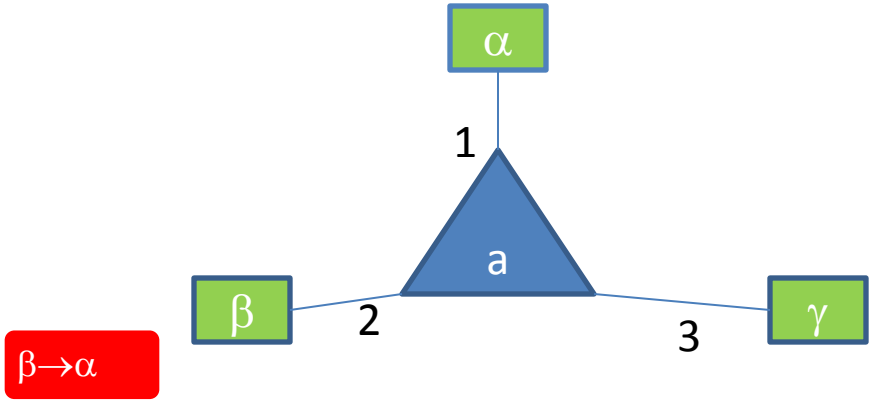
- <controller> ::= <reld>* <evnt>
- <reld> ::= **rel** <**rid**> (<**tid**>*) // auxiliary relations
- <evnt> ::= **packetIn** (**sid**, **pid**, <pr>) $\Rightarrow$ <com>
- <pr> ::= **port(int)**
- <com> ::= **skip**
  | **send(**<pr>**)**
  | **install (sid**, **pid**, <pr>, <opr>**)** // update flow table
  | **rid.insert(**<exp>***)** // update auxiliary relations
  | **if rid(**<exp>***) then** <com>* **else** <com>*
  | **if rid(**<exp>***) then** <com>*
  | <com> **;** < com>
- <opr> ::= <pr> |**none** // drop the package
- <exp> ::= **id** | exp. **id** | <pr>

Learning Switch with 3 ports

```
rel connected (Sw, Pr, Ho)
PacketIn(s, p, port(1)) ->
  connected.insert (s, port(1), p.src)
  if connected(s, port(2), p.dst) then {
     send (port(2))
     install(s, p, port(1),  port(2))
  }
 else if  connected(s, port(3), p.dst) then {
     send (port(3))
     install(s, p, port(1),  port(3))
  }
  else  { // flood
       send (port(2))
       send (port(3))
          }
PacketIn(s, p, port(2)) -> …
PacketIn(s, p, port(3)) ->  …
```

The semantics of the controller

- What is the meaning of package sent by a given host?
  - A set of paths
- Example: Learning Switch



The semantics of the controller

- What is the meaning of package sent by a given host?
  - A set of paths
- Dynamically changed
  - Even for fixed topology
- Unbounded length
- But can it be defined?

The State of a switch

- The switch table is a relation between packets input and output ports

input port output port

- $FT = \mathrm{Sw} \rightarrow \mathrm{P}(\mathrm{Pk} \times \mathrm{Pr} \times \mathrm{Pr} \cup \{\mathrm{none}\})$
- Updated by the controller
- Actual nodes depend on the topology graph

The Semantics of Expressions

- <exp> ::= **id** | exp.**id** | <pr>
- Val = Int $\cup$ Pr $\cup$
  {P(T$[\![t_1]\!] \times$ … T$[\![t_k]\!]$ | t_1, …, t_k are valid types}
- Controller State $\sigma \in \Sigma$ such that σ: Var $\rightarrow$ Val
- E$[\![id]\!]$ σ = σ id
- E$[\![exp.id]\!]$ σ = F$[\![id]\!]$ (E$[\![e]\!]$ σ)
- E$[\![port(n)]\!]$ σ = n

The Meaning of Commands

- <com> ::= **skip**
  | **send(**<pr>**)**
  | **install (sid, pid,** <pr>, <opr>**)**
  | **rid.insert(**<exp>*)
  | **if RID(**<exp>*) **then** <com>* **else** <com>*
  | **if RID(**<exp>*) **then** <com>*
  | <com> **;** < com>
- <opr> ::= <pr> |**none**
- **C[[]]: <com>** $\rightarrow (\Sigma \times FT) \rightarrow (\Sigma \times FT \times P(Pr \cup \{none\})$

  input-state output

Atomic Commands

- $C[\![\textbf{skip}]\!]\,\langle \sigma, ft\rangle = \langle \sigma, ft, \emptyset\rangle$
- $C[\![\textbf{send}(pr)]\!]\,\langle \sigma, ft\rangle = \langle \sigma, ft, \{E[\![pr]\!]\}\,\rangle$
- $C[\![\textbf{install}(sw, pk, pr_{in}, pr_{out})]\!]\langle \sigma, ft\rangle =$
  $\Big\langle \sigma,$
  $ft[sw \mapsto ft(sw) \cup \{\langle pk, E[\![pr_{in}]\!], E[\![pr_{out}]\!]\rangle\},$
  $\emptyset\Big\rangle$
- $C[\![r.\textbf{insert}(\underline{e})]\!]\,\langle \sigma, ft\rangle =$
  $\Big\langle \sigma\big[r \mapsto \sigma\, r \cup \{\langle\, E[\![\underline{e}]\!]\rangle\}\big], ft, \emptyset\Big\rangle$

Conditional Commands

- $C[\![\textbf{if } r(\underline{e}) \textbf{ then } c_1 \textbf{ else } c_2]\!]\,\langle \sigma, ft\rangle =$

$$\begin{cases} C[\![c_1]\!]\,\langle \sigma, ft\rangle & \text{If } \langle E[\![\underline{e}]\!]\rangle \in \sigma\ r \\ C[\![c_2]\!]\,\langle \sigma, ft\rangle & \text{If } \langle E[\![\underline{e}]\!]\rangle \notin \sigma\ r \end{cases}$$

Sequential Composition

- $C[\![c_1 ; c_2]\!] \langle \sigma, ft \rangle =$
  let $\langle \sigma', ft', prs_1 \rangle = C[\![c_1]\!] \langle \sigma, ft \rangle$
  $\langle \sigma'', ft'', prs_2 \rangle = C[\![c_2]\!] \langle \sigma', ft' \rangle$
  in
  $\langle \sigma'', ft'', prs_1 \cup prs_2 \rangle$

Semantics of Events

- **G⟦⟧: <evnt>** $\rightarrow$ (Sw $\times$ Pk $\times$ Pr) $\rightarrow$ P((Σ $\times$ FT) $\times$ (Σ $\times$ FT $\times$ P(Pr $\cup${none}))

- G⟦packetIn(s, p, i) $\Rightarrow$ c⟧ $\langle$sw, pk, ip$\rangle$ = R where

$$\langle \sigma, ft \rangle \; R \; \langle \sigma', ft', ports \rangle$$

Iff

$$(\neg \exists op : Pr. \langle pk, ip, op \rangle \in ft) \wedge$$

$$C[\![c]\!]\langle \sigma[s \mapsto sw, p \mapsto pk, i \mapsto ip], ft \rangle = \langle \sigma', ft', sp \rangle$$

Packet Histories

- Packets can influence the routing of other packets
- Histories can be seen as sequences of packet transmissions
- HST= $(\mathrm{Sw} \times \mathrm{Pr} \times \mathrm{Pk} \times (\mathrm{Pr} \cup \{\mathrm{none}\}))^*$

Small-step semantics (Controller)

- $\Rightarrow_{ctrl} : (\Sigma \times FT \times HST) \times (\Sigma \times FT \times HST)$
- $\langle \sigma, ft, h \rangle \Rightarrow_{ctrl} \langle \sigma', ft', h' \rangle$ iff

$\exists sw : Sw, pk : Pk, ip : Pr, sp : P(Pr).$

$\langle \sigma, ft, sw \rangle \left(G[\![evnt]\!] \langle sw, pk, ip \rangle \right) \langle \sigma', ft', sp \rangle \wedge$

$h' = h \cdot \langle sw, ip, pk, j \rangle_{j \in sp \vee (sp = \varnothing \wedge j=none)}$

Small-step Semantics (Switch)

- $\Rightarrow_{sw} : (\Sigma \times FT \times HST) \times (\Sigma \times FT \times HST)$
- $\langle \sigma, ft, h \rangle \Rightarrow_{switch} \langle \sigma', ft', h' \rangle$ iff

  $\sigma = \sigma' \wedge ft = ft' \wedge$

  $\exists sw : Sw, pk : Pk, ip : Pr, op : Pr \cup \{none\}.$

  $\langle pk, ip, op \rangle \in ft\ sw \wedge$

  $h' = h \cdot \langle sw, ip, pk, op \rangle$

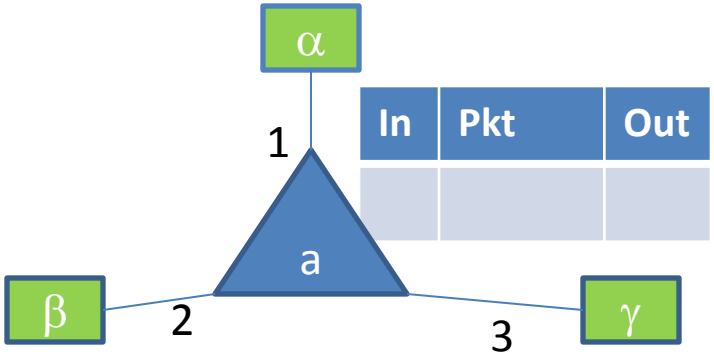
Executions

- Combined step semantics:
  - $\Rightarrow = \Rightarrow_{ctrl} \cup \Rightarrow_{switch}$
- A sequence of event processing steps has the from
  - $a_1 \Rightarrow a_2 \Rightarrow \ldots \Rightarrow a_n$

Feasible Histories

- Given a topology graph G over
  $V = Ho \cup (Sw \times Pr)$
- A history h is **feasible** w.r.t. a given topology graph G iff for any packet $pk \in Pk$:
  - any two consecutive entries for p in h:
    - $\langle sw_1, ip_1, pk, op_1 \rangle$ and $\langle sw_2, ip_2, pk, op_2 \rangle$
    - there exists an edge between $\langle sw_1, op_1 \rangle$ and $\langle sw_2, ip_2 \rangle$ in G

Example



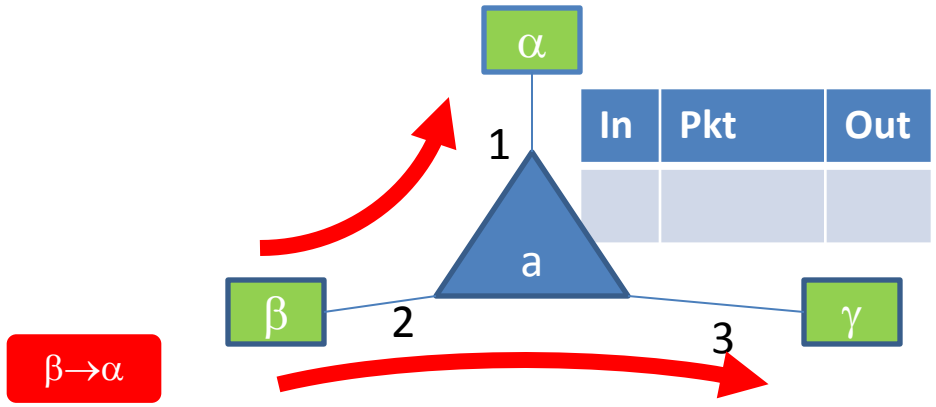
In	Pkt	Out

Port in	Packet	Port out

connected =

Port	Host

Example

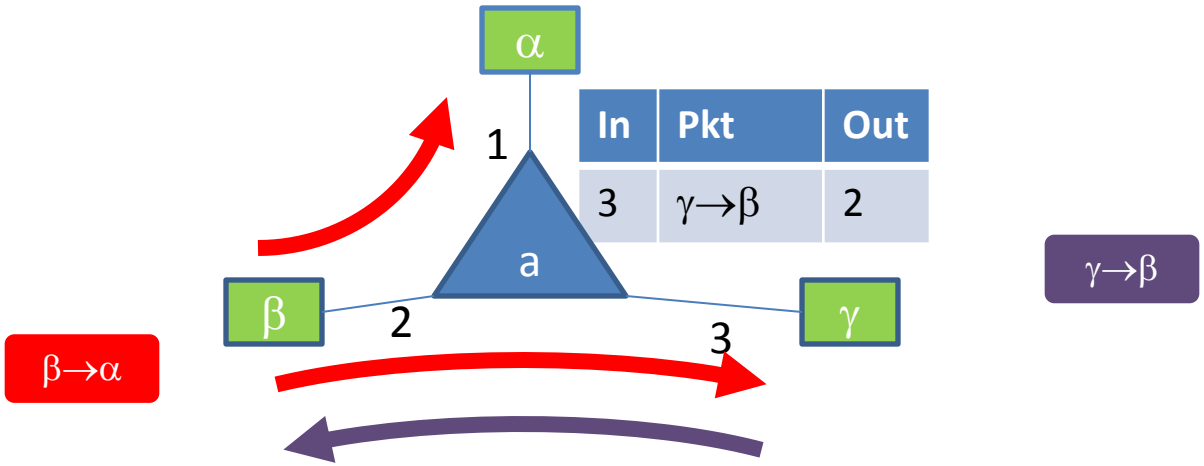


Port in	Packet	Port out
2	β→α	1
2	β→α	3

connected =

Port	Host
2	β

Example



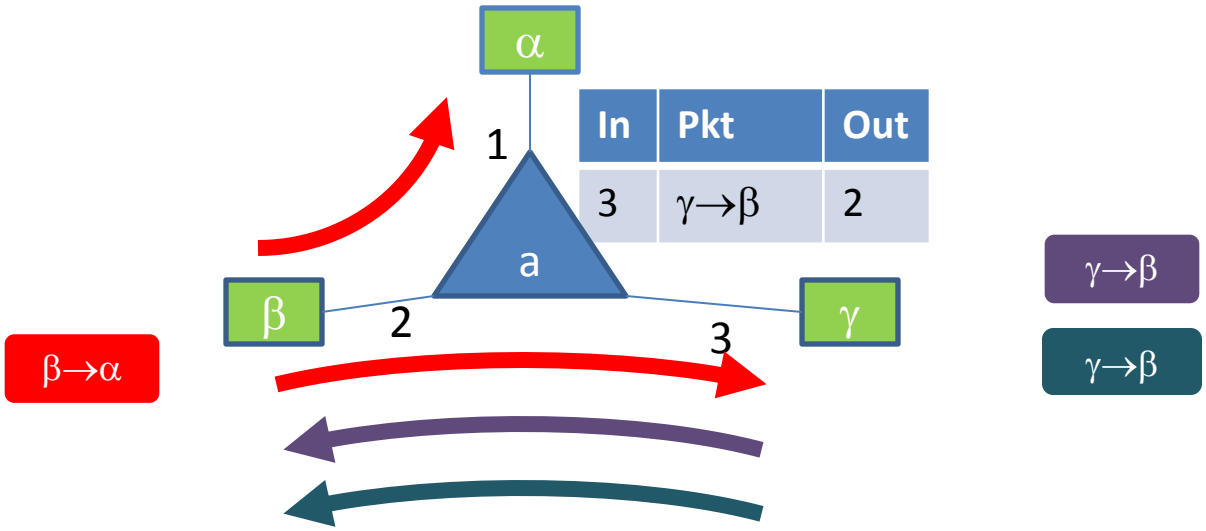
In	Pkt	Out
3	γ→β	2

Port in	Packet	Port out
2	β→α	1
2	β→α	3
3	γ→β	2

connected =

Port	Host
2	β
3	γ

Example



Port in	Packet	Port out
2	β→α	1
2	β→α	3
3	γ→β	2
3	γ→β	2

connected =

Port	Host
2	β
3	γ

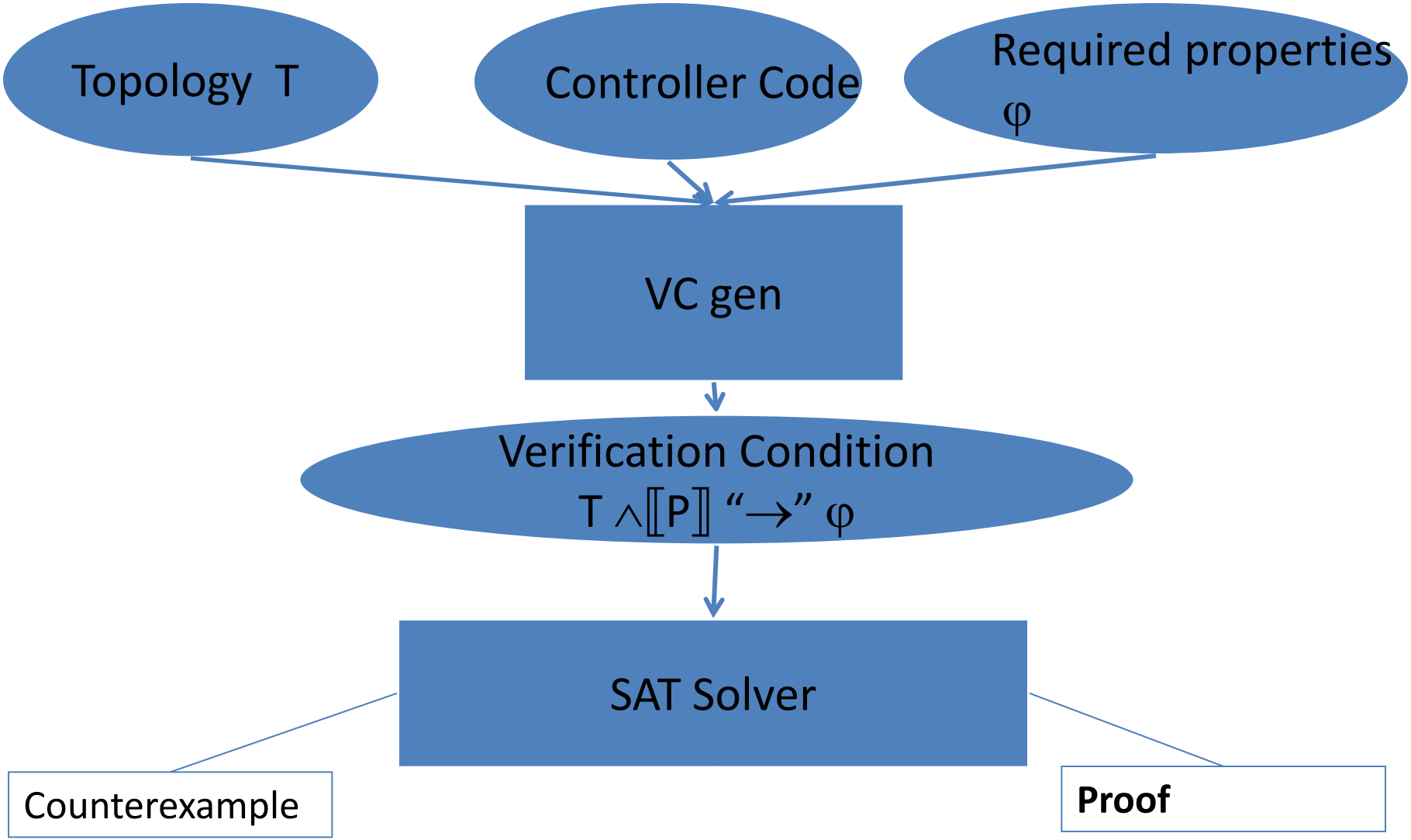
Properties of the Semantics

- Compositional
- Allows free packets
- Assume that (controller) actions executed atomically
  - Ignores delays in switch rule instantiations

Useful Programming Language Tools

- Interpreter
- Compiler
- Parser
- Type Checker
- Static Program Analysis
- Verification Tool
- Dynamic Program Analysis
  - Model checker

Verification Process



Interesting Network Properties

Property	Meaning
Connectivity	Every packet eventually reaches its destination
No forwarding loops	A switch sw never receives a packet sent by sw
No black holes	No packet should be dropped in the network
Access control	No paths between certain hosts of certain packets
Direct paths	Once a packet reached its destination future packets are not going to the controller
Strict direct paths	Once two packets travel both ways between a source and destination
Data structure integrity	The controller data structures ``correctly'' records the network states