SCL: Simple Coordination Layer

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Software Defined Networks

- Forwarding implemented by switches.
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- Rules computed by controllers.
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- Rules depend on policy and network state.
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- Rules depend on **policy** and **network state**.
- **Policy**: What paths are acceptable?
Software Defined Networks

- Forwarding implemented by switches.
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- Rules depend on **policy** and **network state**.

  - **Policy**: What paths are acceptable?
  - **Network State**: Current state of links and switches
How to build controllers?
Single Image Controllers

- Controller runs on a single server.
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- Examples: Nox, Pox, Ryu, etc.
Single Image Controllers: Assumptions

- The controller observes a sequence of events.
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  - **Network state** computed using event sequence.
Single Image Controllers: Assumptions

- The controller observes a sequence of events.
- **Network state** computed using event sequence.
- Applications react to sequence of events.

**Diagram:**
- Controller
- Switch A
- Switch B
- Time

Events: $e_1$, $e_0$
Single Image Controllers: Assumptions

- The controller observes a sequence of events.
- **Network state** computed using event sequence.
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- Events and updates sent over TCP channels.
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- Updates to different switches can be reordered.
How to handle controller failures, scale controllers, etc.?
Events can be reordered.
Updates can be reordered.
Events and updates sent over reliable channels - TCP.
Controllers observe a consistent sequence of events.
Applications react to sequence of events.
Network state computed using event sequence.

How to handle controller failures, scale controllers, etc.?

Move to **distributed controllers**.
How to build distributed controllers?
Why is this Harder?

- Event *ordering* can differ across controllers.
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- Rules must converge despite this reordering.
- Two ways to handle this
  - Algorithms are correct despite reordering.
  - Mechanisms so controllers agree on ordering.
- Rely on **ordering mechanisms** for generality.
- How to implement event ordering?
Consensus: Protocol to get agreement on a value.

Controller I

Controller II

Switch A

Switch B

Coalition: [Controller I, Controller II, Switch A, Switch B]
Canonical Solution: Consensus

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- Rely on consensus to agree on event order.
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- Controllers are Replicated State Machines.
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• Rely on **consensus** to agree on event order.

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• Can use same algorithms as single image controller.

• Controllers are **Replicated State Machines**.

• Adopted by **Onix**, **ONOS**, etc.
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- Adopted by Onix, ONOS, etc.

How to implement consensus?
Canonical Consensus Mechanism

- Several algorithms in use - **ZAB**, **Raft**, **Paxos** variants (e.g., MultiPaxos)
Canonical Consensus Mechanism

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- Leader receives all network events - decides on order.

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- Must wait for a **quorum** of controllers to confirm replication.
- Once quorum has confirmed delivers events to application.
Canonical Consensus Mechanism

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  • If leader fails protocol appoints new leader.
  • Protocol must ensure leader is one with newest data.
  • Quorum replication ensures order cannot be forgotten.
  • Controller can reconstruct state by replaying events.
Canonical Consensus Mechanism: Limitations

• Fault Tolerance: at least one partition fails during network partitions.
Canonical Consensus Mechanism: Limitations

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- Scalability: Worse performance worsens with more controllers.
Canonical Consensus Mechanism: Limitations

- Fault Tolerance: at least one partition fails during network partitions.
- Scalability: Worse performance worsens with more controllers.
- Control Plane Requirements: Performance is sensitive to losses, latency, etc.
Is consensus required?
Consensus Assumption

- **Network state** (topology and forwarding table) resides in **controllers**.
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- RSMs ensure **network state** is **not lost** when controllers fail.
Consensus Assumption

- **Network state** (topology and forwarding table) resides in controllers.
- RSMs ensure **network state** is not lost when controllers fail.
  - Similar to distributed **key value stores**.
Consensus Assumption is Wrong

But we can query the network to discover current network state.
Consensus Assumption is Wrong

But we can query the network to discover current network state.

Safe to lose network state!
Distributed Controllers: An Alternative

- Assume all controllers agree on policy.
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- Each controller
Distributed Controllers: An Alternative

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  1. Periodically queries network state.
Distributed Controllers: An Alternative

1. Periodically queries network state.
2. Uses state and policy to compute updates.

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2. Compute Updates
Policy Controller

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Distributed Controllers: An Alternative

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  1. Periodically queries network state.
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  3. Installs updates in the network.
- Converges assuming quiescence.

Network

Policy Controller

Policy Controller
Challenges

- Programming model: how to write control applications?
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- Programming model: how to support existing event based algorithms?
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• Policies: what classes of policies can be implemented using this mechanism?
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SCL: Programming Model and Architecture
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- Builds on standard single-image controller (Pox).
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- Switch Agents implement querying and channels.
SCL: Programming Model and Architecture

- Builds on standard single-image controller (Pox).
- Switch Agents implement querying and channels.
- Controller Proxies ensure convergence.
SCL Controller Requirements

- **Deterministic**: Controllers compute the same rule for given network state.
SCL Controller Requirements

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- **Idempotent**: The process of computing and updating rules is idempotent.
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- **Proactive Applications**: Compute rules based on network state not packet-ins.
SCL Controller Requirements

- **Deterministic**: Controllers compute the same rule for given network state.
- **Idempotent**: The process of computing and updating rules is idempotent.
- **Proactive Applications**: Compute rules based on network state not packet-ins.
- **Triggered Updates**: Can trigger rule recomputation based on event log.
SCL Proxies and Controllers

Agent
Switch A

Agent
Switch B

Agent
Switch C

A Table  B Table  C Table

A Table  B Table  C Table

A Table  B Table  C Table

Proxy

Controller
SCL Proxies and Controllers

- Proxies maintain a log of all prior network events.
SCL Proxies and Controllers

- Proxies maintain a log of all prior network events.
- All switch events are sent to all proxies.
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- Proxy triggers controller computation.
SCL Proxies and Controllers

- **Proxies** maintain a log of all prior network events.
- All switch events are sent to all **proxies**.
- **Proxy** triggers controller computation.
- Computation based on current log.

![Diagram of SCL Proxies and Controllers]

- A Table
- B Table
- C Table

Agent

Switch A

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SCL Proxies and Controllers

- Proxies maintain a log of all prior network events.
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- All switch events are sent to all proxies.
- Proxy triggers controller computation.
- Computation based on current log.
- Controller sends updates to proxy.
- Proxy maintains state about installed rules.
- Deduplicates updates before applying them.
SCL Proxies and Controllers: Challenges

- **Agreement:** Proxies must eventually agree on order.
SCL Proxies and Controllers: Challenges

- **Agreement:** Proxies must eventually agree on order.
- **Agreement:** Must eventually agree on the set of events.
SCL Proxies and Controllers: Challenges

- **Agreement**: Proxies must eventually agree on order.
- **Agreement**: Must eventually agree on the set of events.
- **Awareness**: Controllers and network state agrees eventually.
Addressing SCL Challenges

- Address these with two mechanisms.
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- **Gossip** between controllers
Addressing SCL Challenges

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• Address these with two mechanisms.

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  • Eventual *agreement* on observed *events*.

  • Also assures *agreement* on *ordering*. 
Addressing SCL Challenges

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• Periodically query network for state.
Addressing SCL Challenges

- Address these with two mechanisms.
  - **Gossip** between controllers
    - Eventual agreement on observed events.
    - Also assures agreement on ordering.
  - Periodically query network for state.
    - Awareness of network state.
Why abandon consensus?
Conceptually Unnecessary

- **RSM assumption**: Truth about network lies in the controller.
Conceptually Unnecessary

- **RSM assumption**: Truth about network lies in the controller.
- **Reality**: Truth about the network lies within the network (dataplane).
Conceptually Unnecessary

- **RSM assumption**: Truth about network lies in the controller.
- **Reality**: Truth about the network lies within the network (dataplane).
  - Packets are processed by dataplane not by controllers.
Improves Performance and Resilience

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What about Route Convergence?

Convergence time in AS1221

CDF

Convergence time in AS1221
What about Route Convergence?

Convergence time in AS1221

Convergence time for fat tree
When Does Everyone Agree?

Convergence time in AS1221
When Does Everyone Agree?

Convergence time in AS1221

Convergence time in Fat Tree
In the Paper

- Proof that gossip and periodic update are sufficient to guarantee convergence.
- Broadcast based in-band control channels.
- Mechanisms for policy update.
- Interaction with other types of policies.
- Other performance results.
<table>
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</tr>
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</tr>
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Related Work

Control Plane Consistency

Serializability
Consensus: ONIX (OSDI’10), ONOS

Data Plane Consistency (Orthogonal)
Related Work

Control Plane Consistency

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Atomic registers: Schiff et al (CCR’16)

Data Plane Consistency (Orthogonal)
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Stronger Semantics
- Exactly-Once: Ravana (SOSR’15)

Data Plane Consistency (Orthogonal)
## Related Work

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Conclusion

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- **Implication**
  - Simplifies controllers.
  - Improves convergence time, responsiveness, robustness.