# Correctness and Performance for Stateful Chained Network Functions

Junaid Khalid[W,G] and Aditya Akella[W]

*This work does not have any affiliation with Google

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# Network Function Virtualization (NFV)

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- Adding ***new functionality***
- Simplifies ***service chaining***

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# Service Chaining

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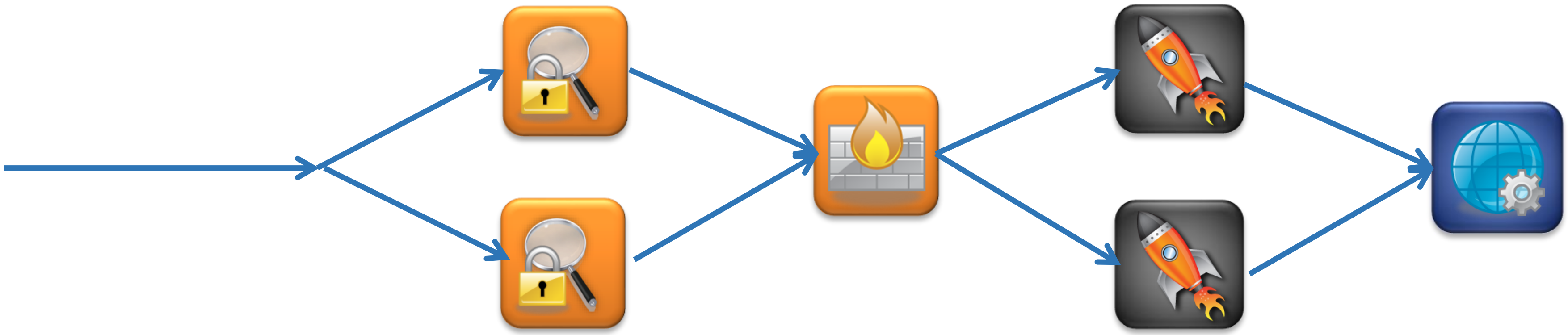

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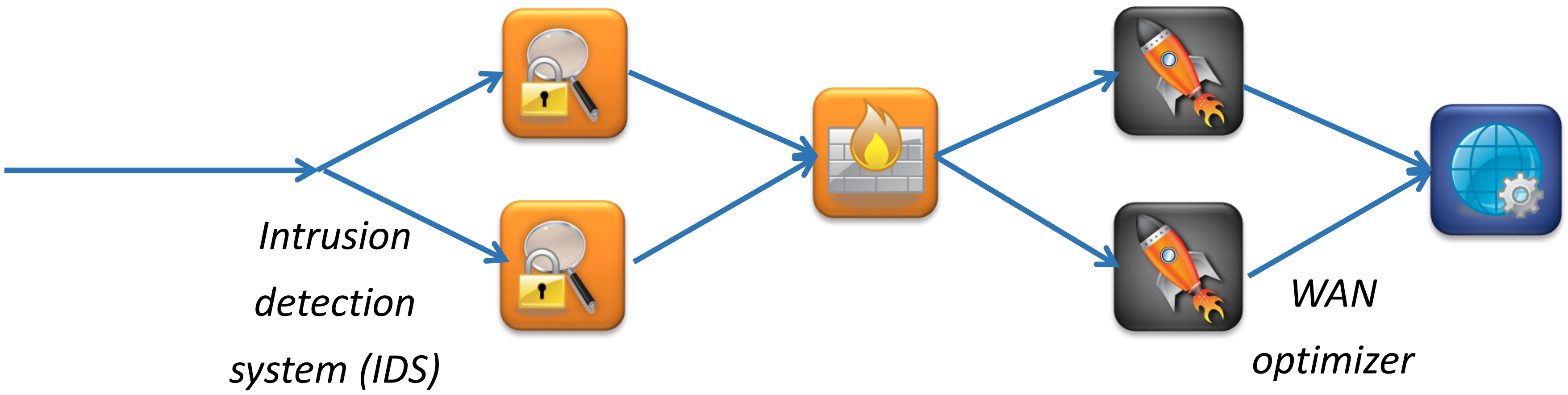

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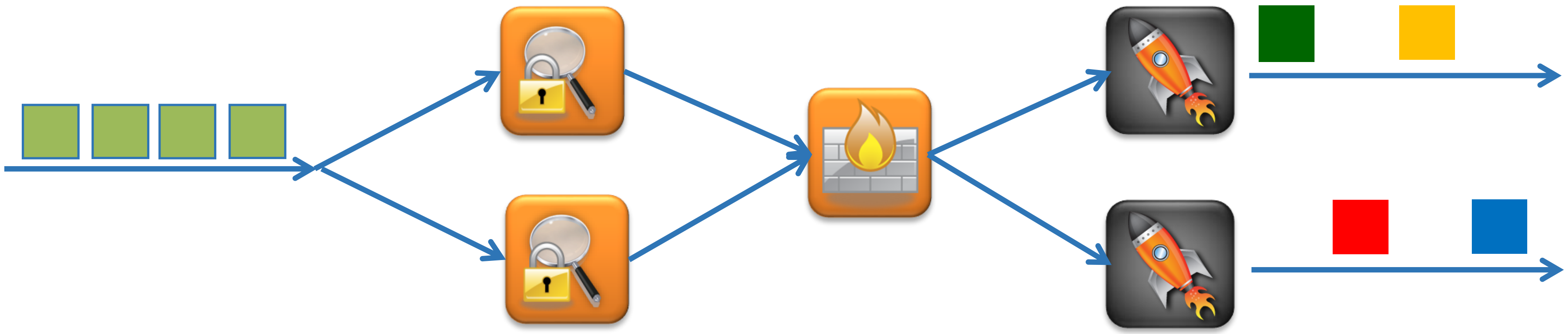

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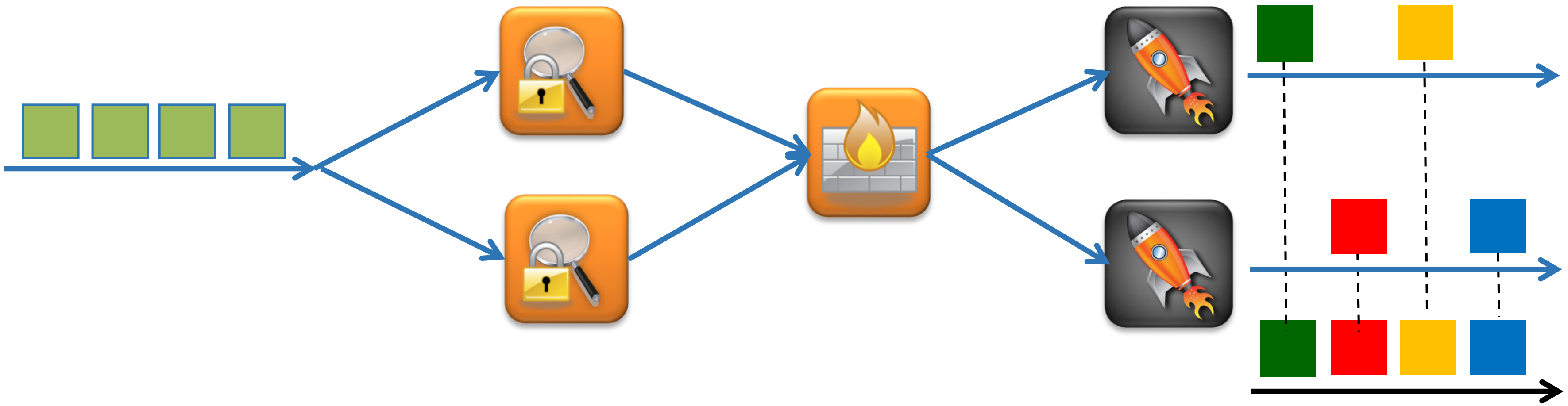

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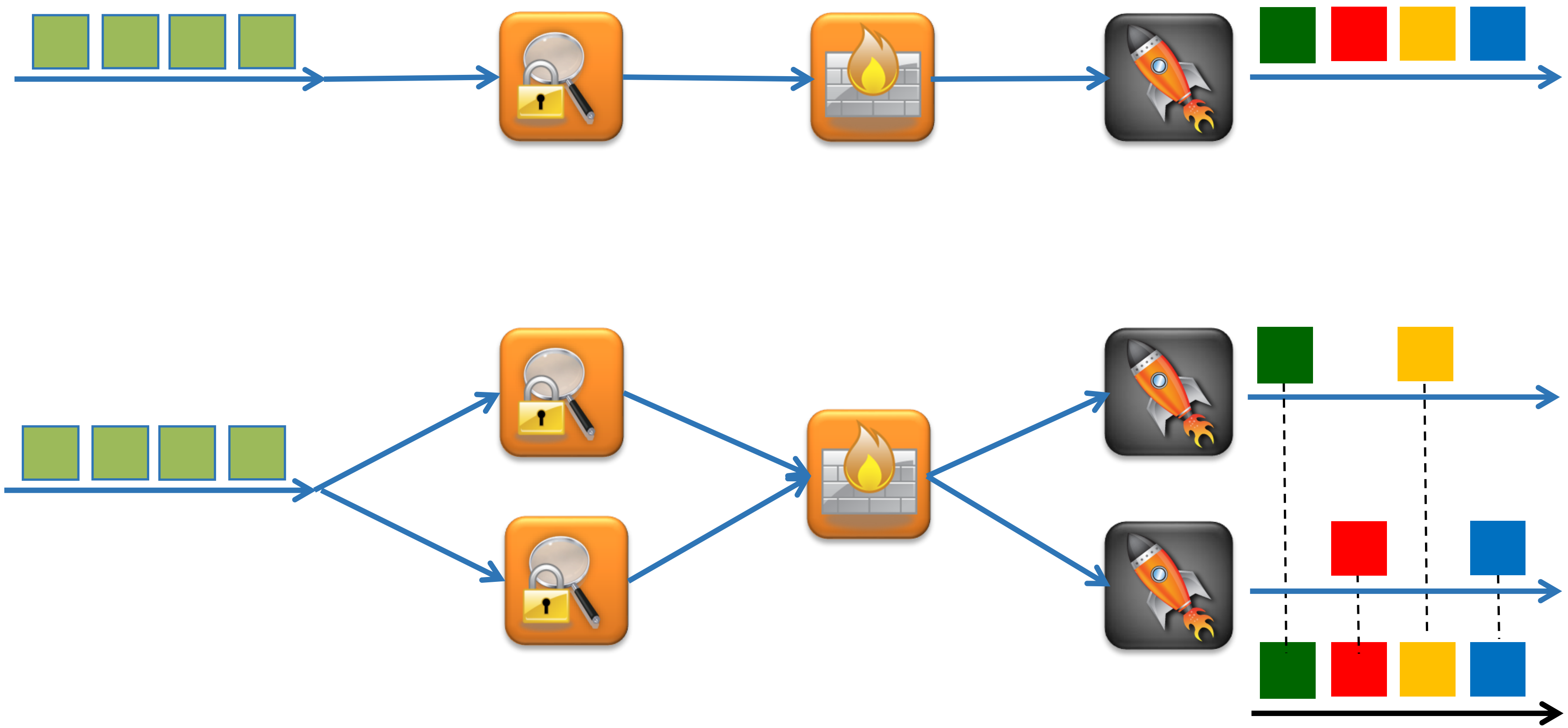

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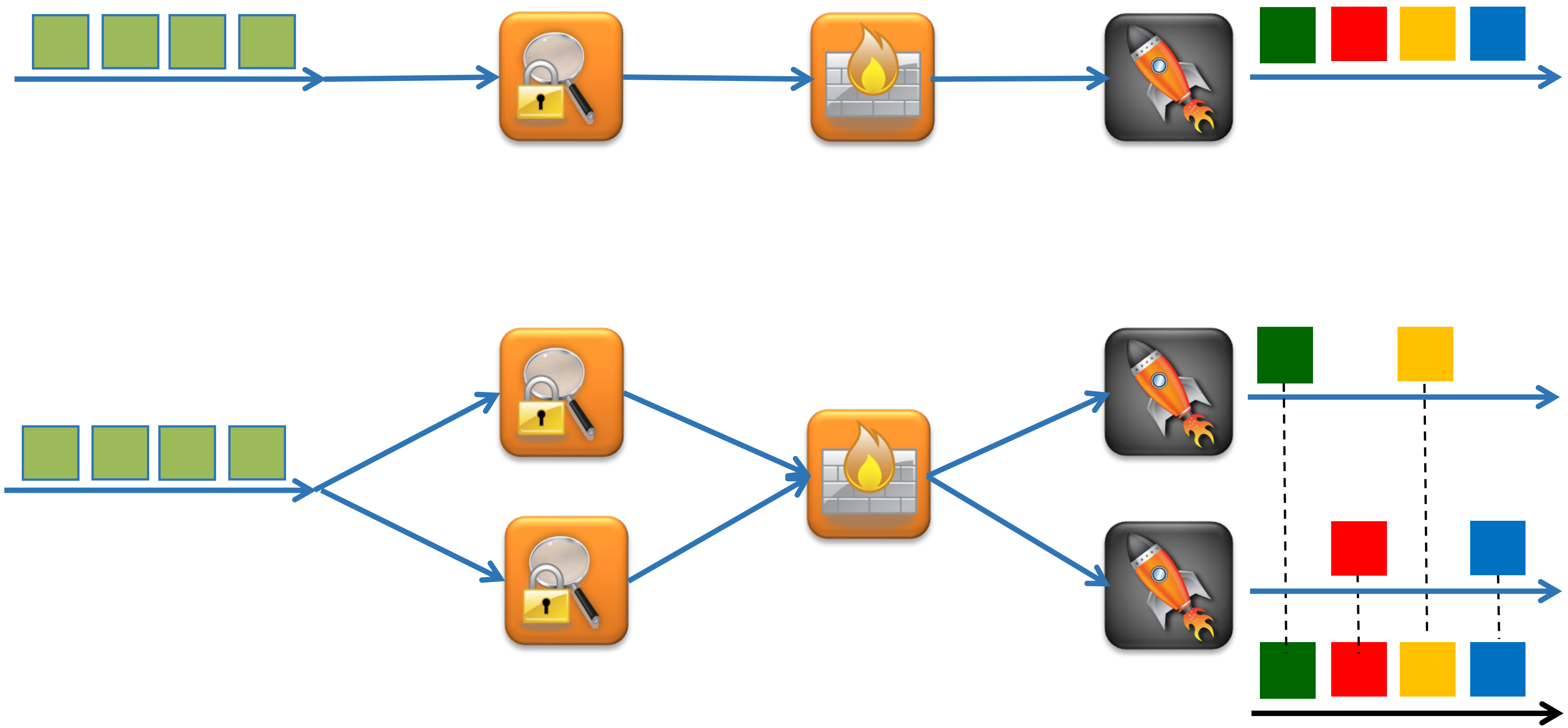
**Chain output equivalence (COE):** for any input the aggregate output of a dynamic set of instances should be equivalent to the output produced by a single instance



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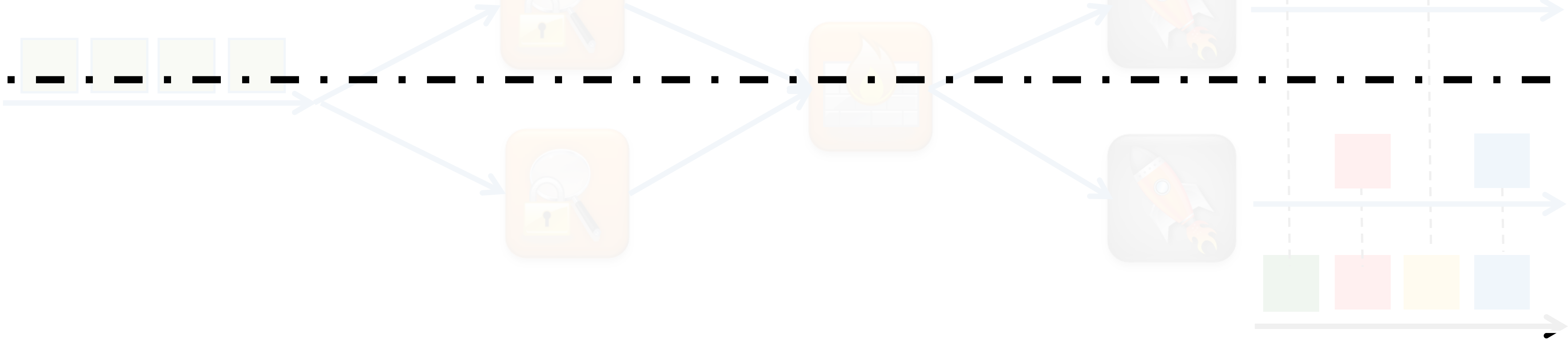
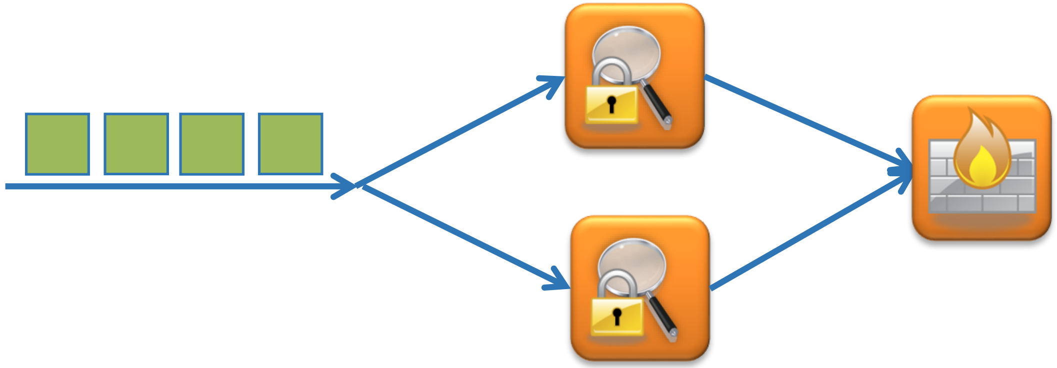
Ensuring COE is challenging: ***NF chain attributes & Dynamic Actions***



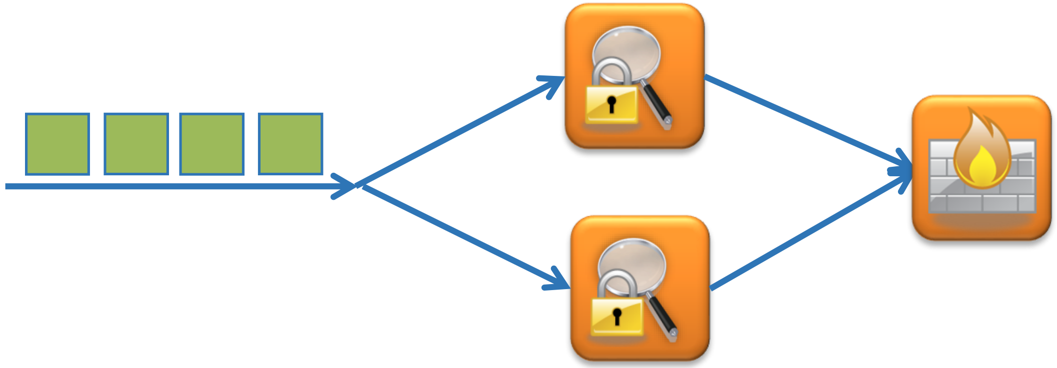
# NF Chain Attributes



# NF Chain Attributes

1. NF statefulness

- Perform sophisticated *stateful* actions on packets/flows



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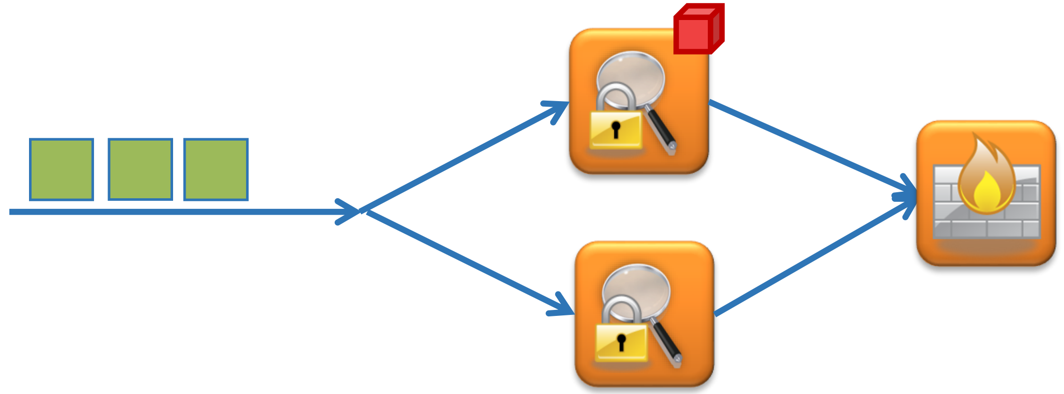

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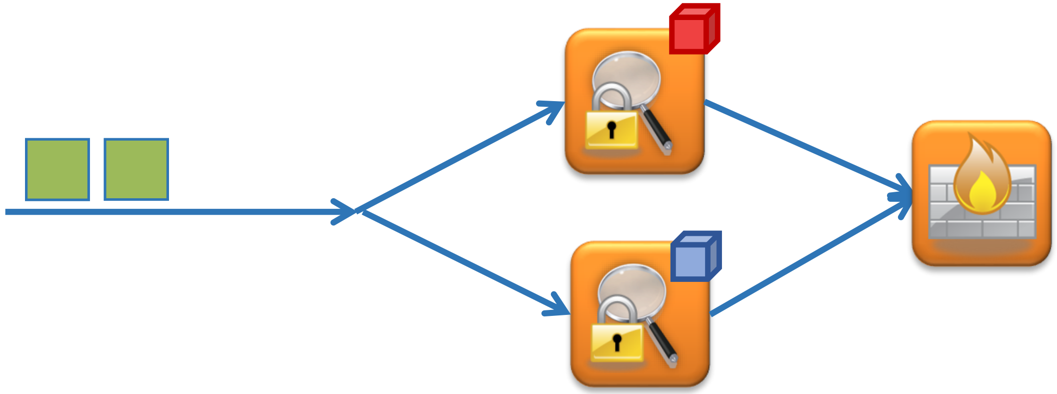

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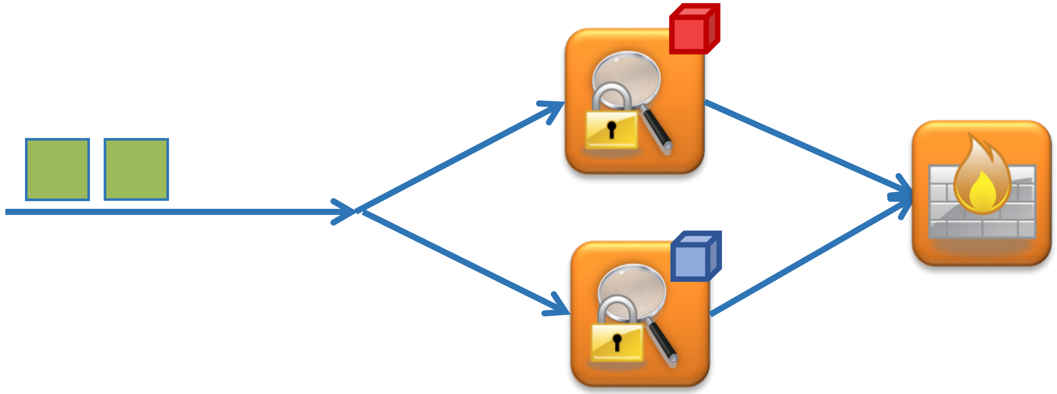

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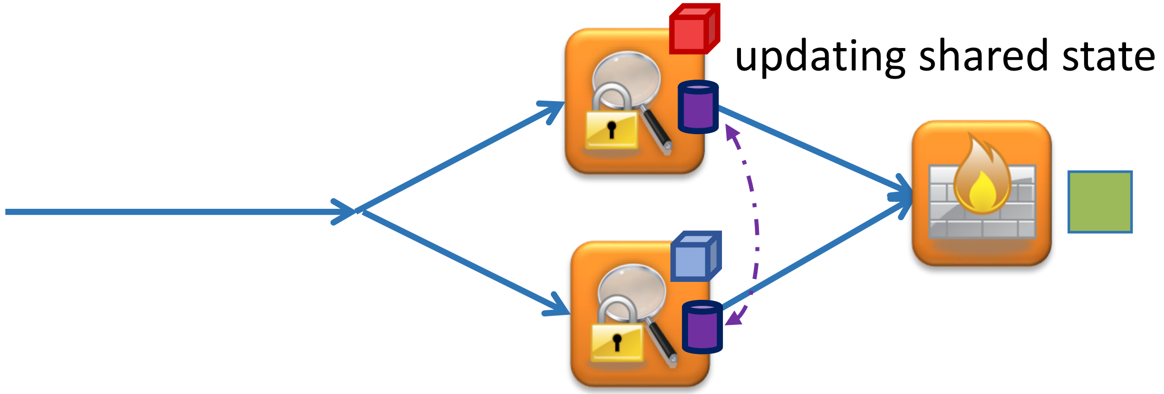

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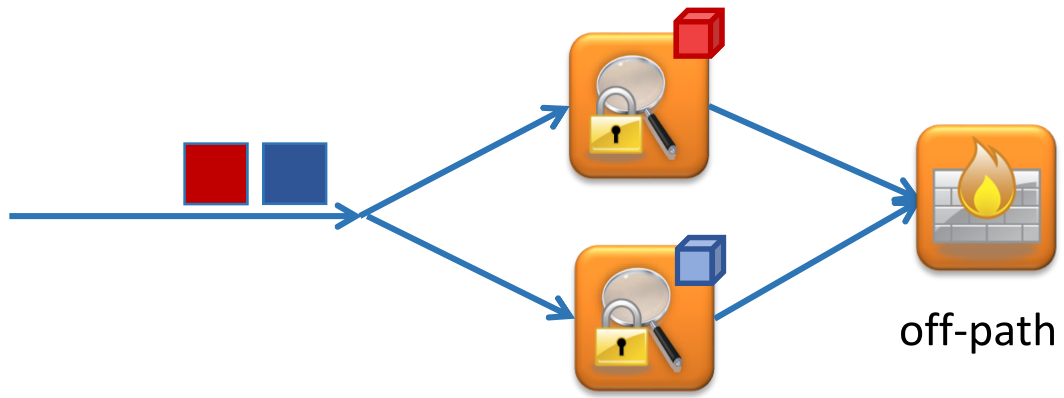

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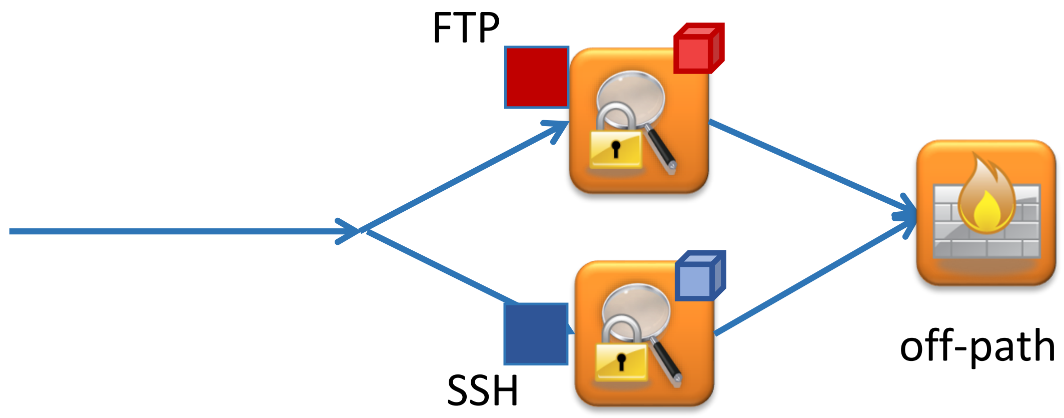

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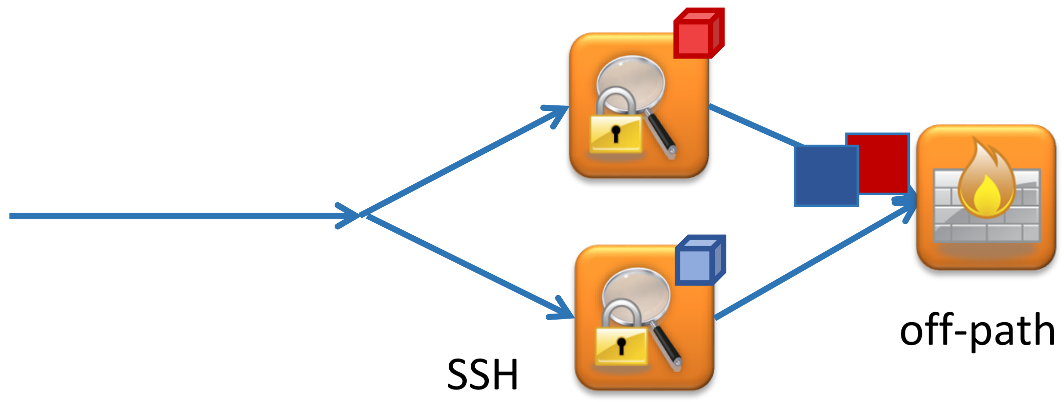

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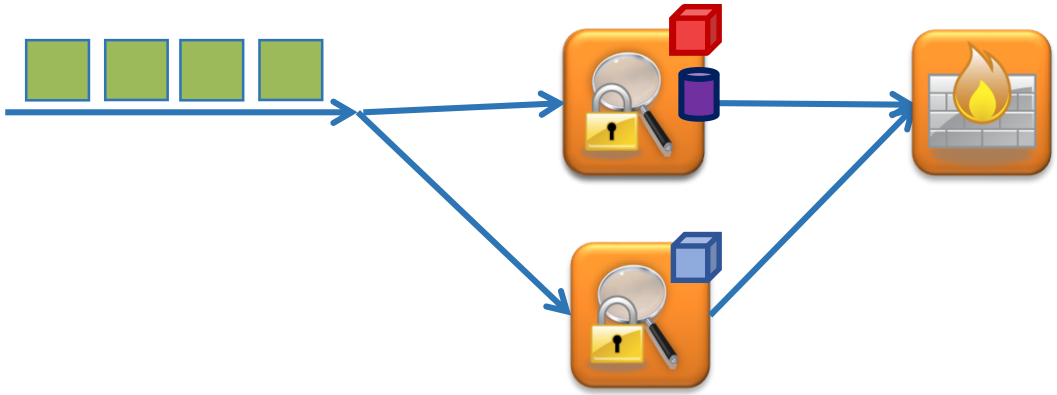

**Key requirements**

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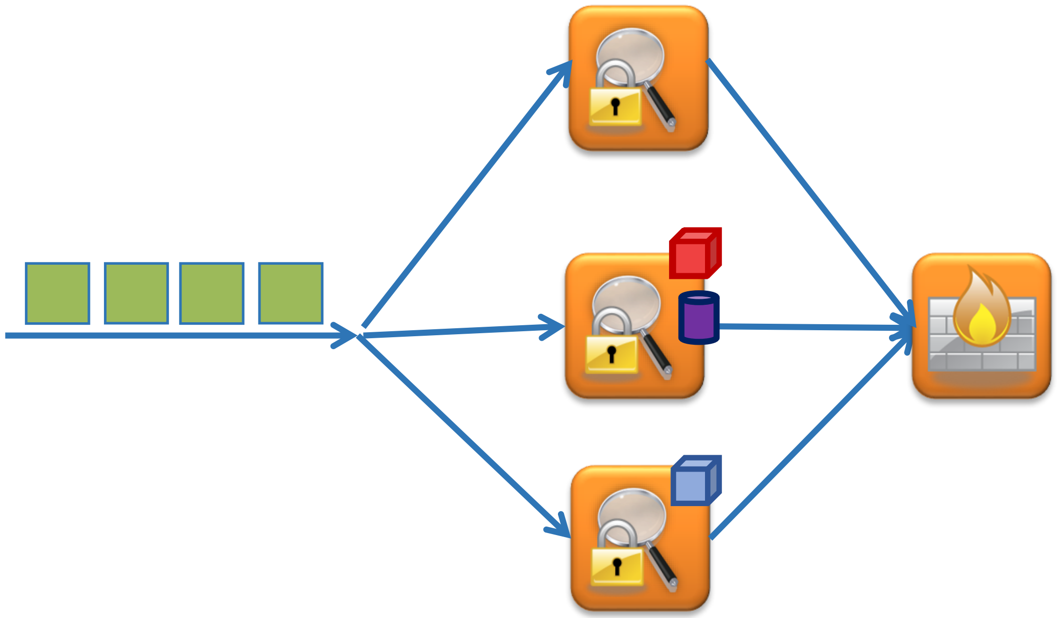
## Load balancing/elastic scaling

- Flows are moved from one instance to another to balance load or handle traffic spikes



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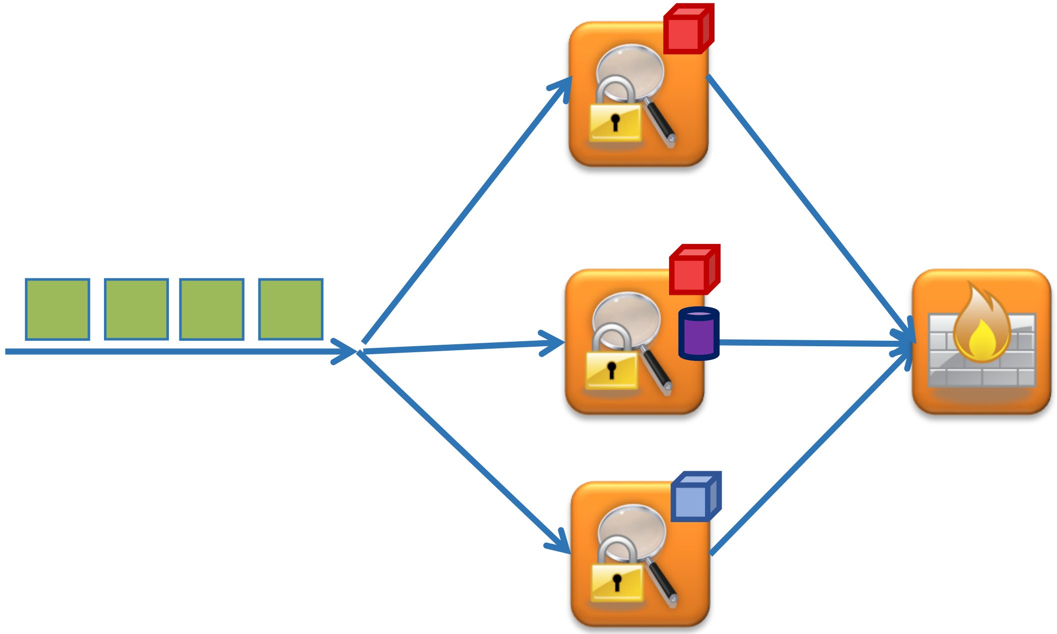

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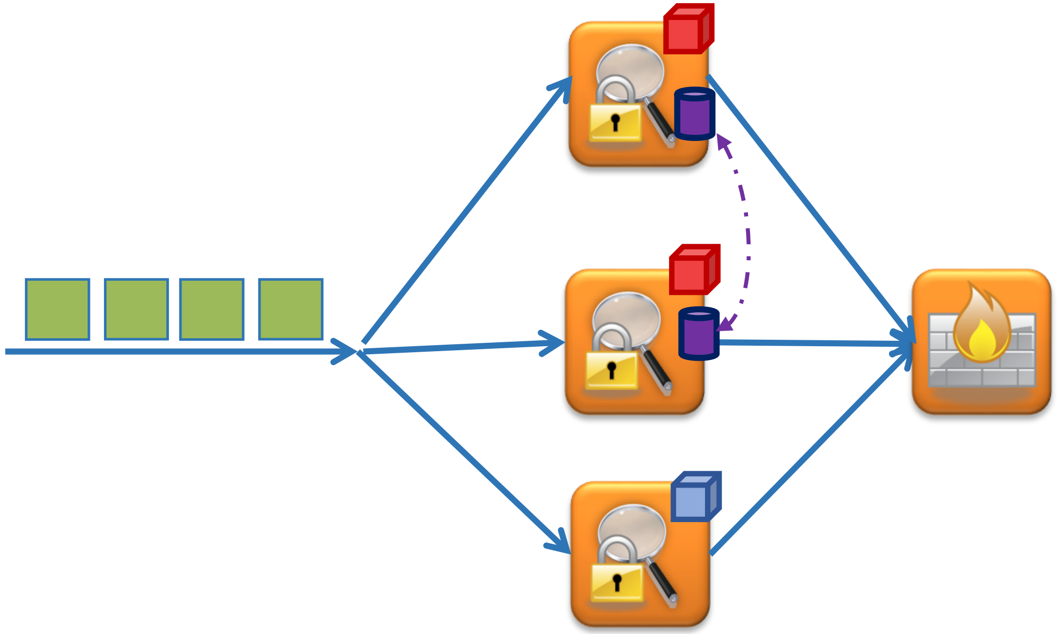

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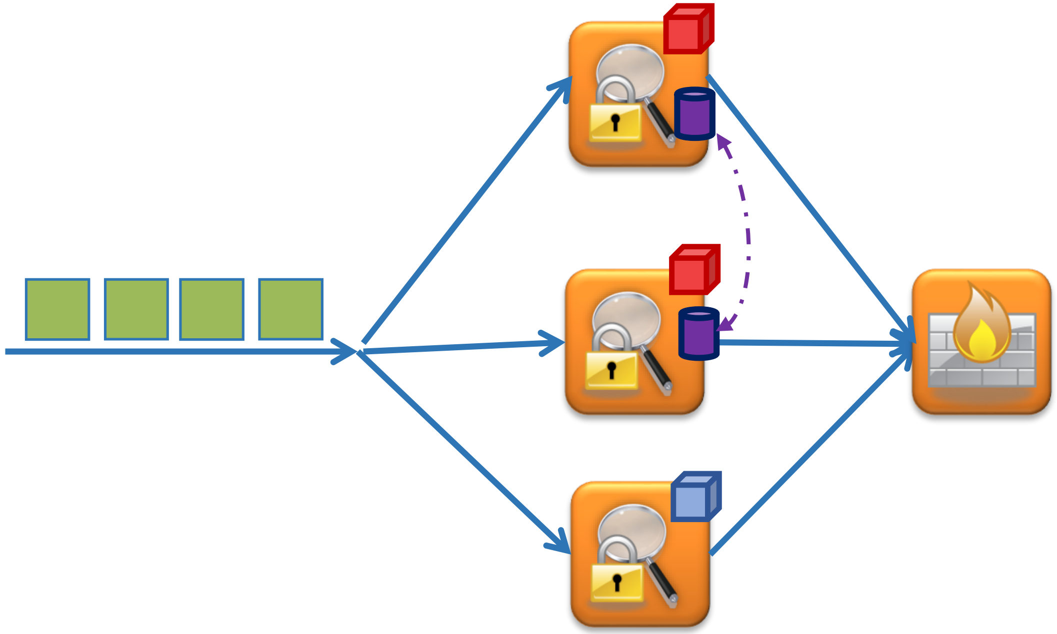

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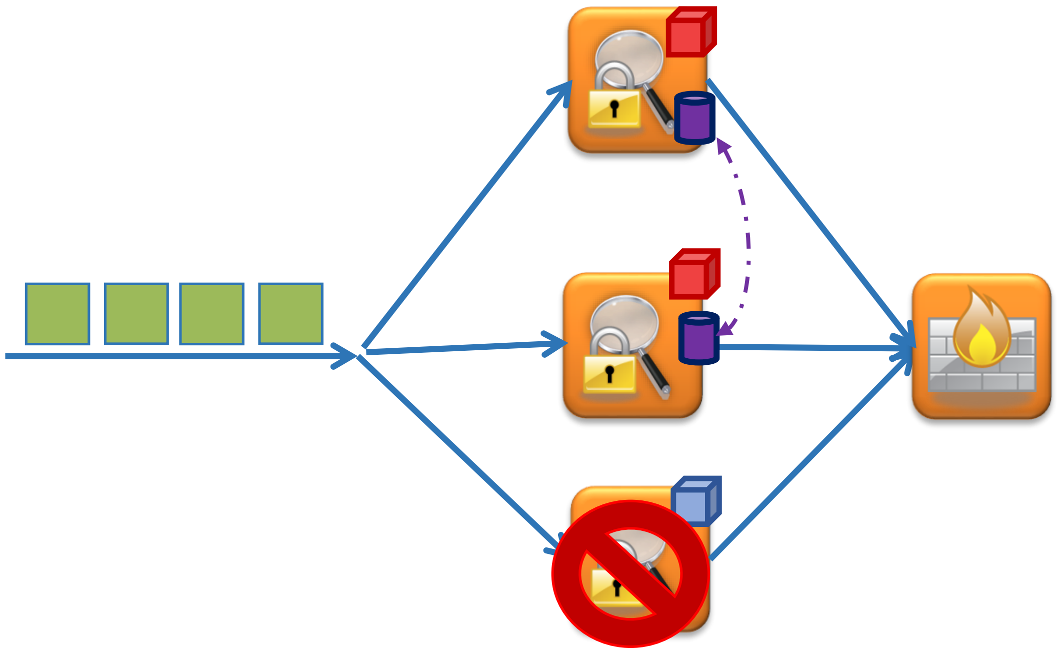

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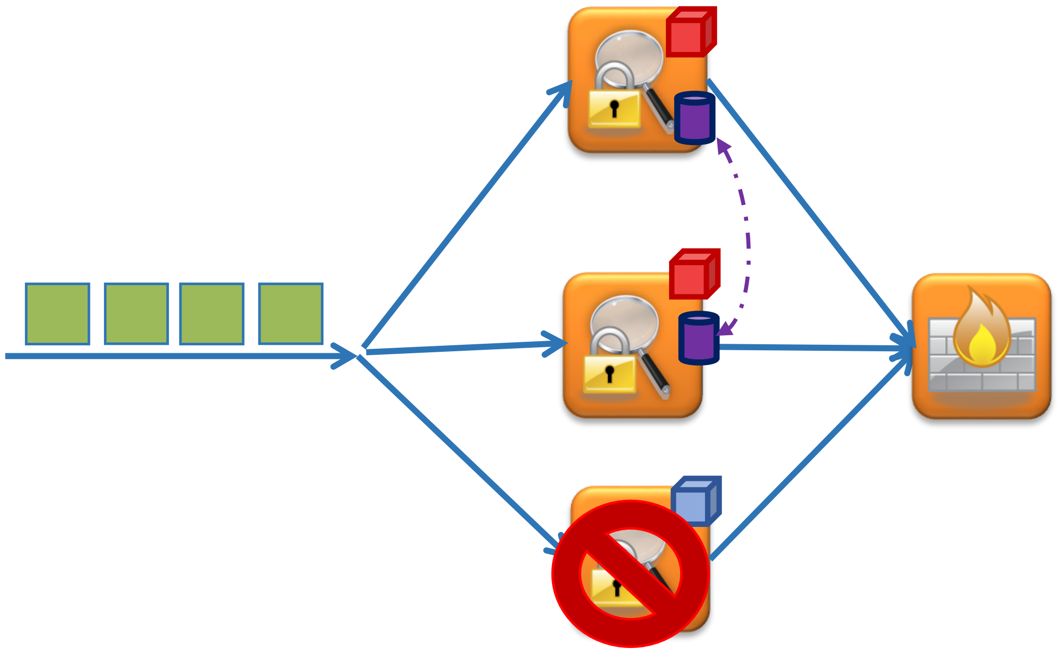
## Failure recovery

- When NF fails, all its state disappears. For fault tolerance, that state needs to be recovered



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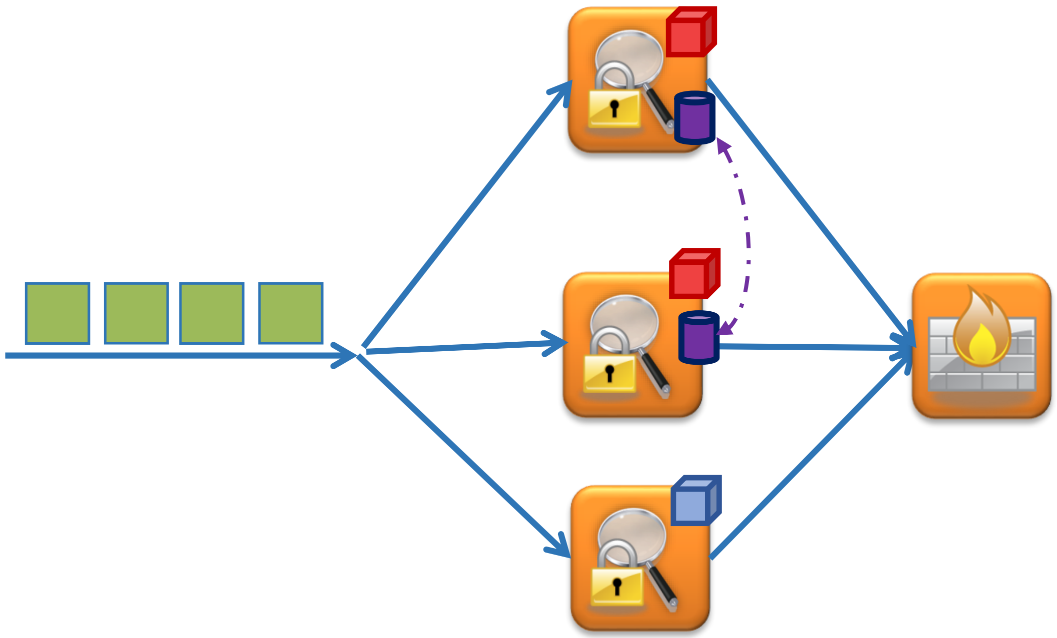

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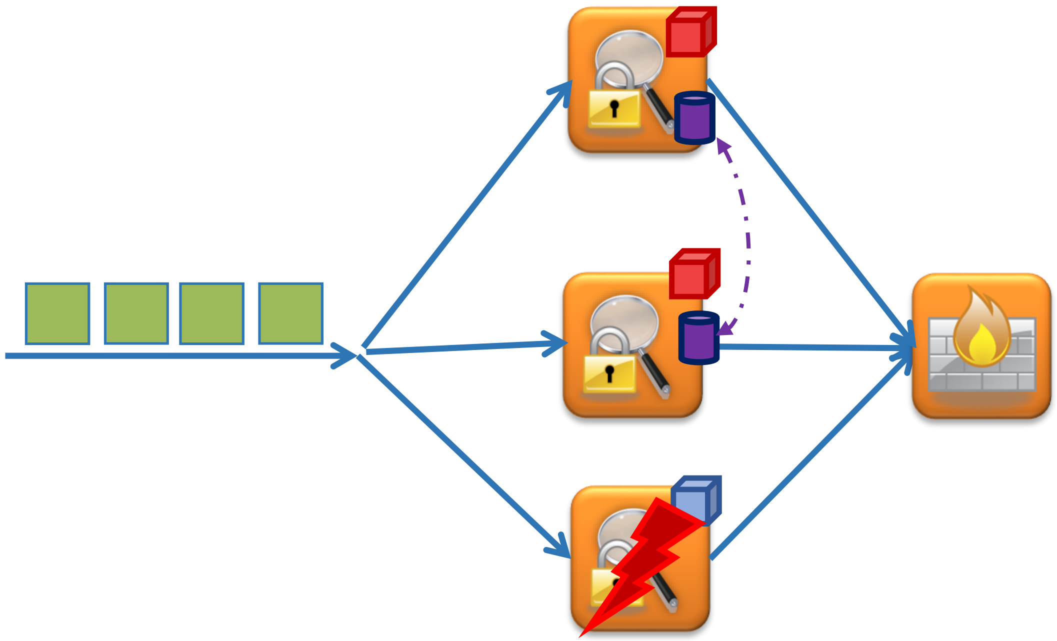
- Clones may be launched to handle a straggler NF (a slow NF)



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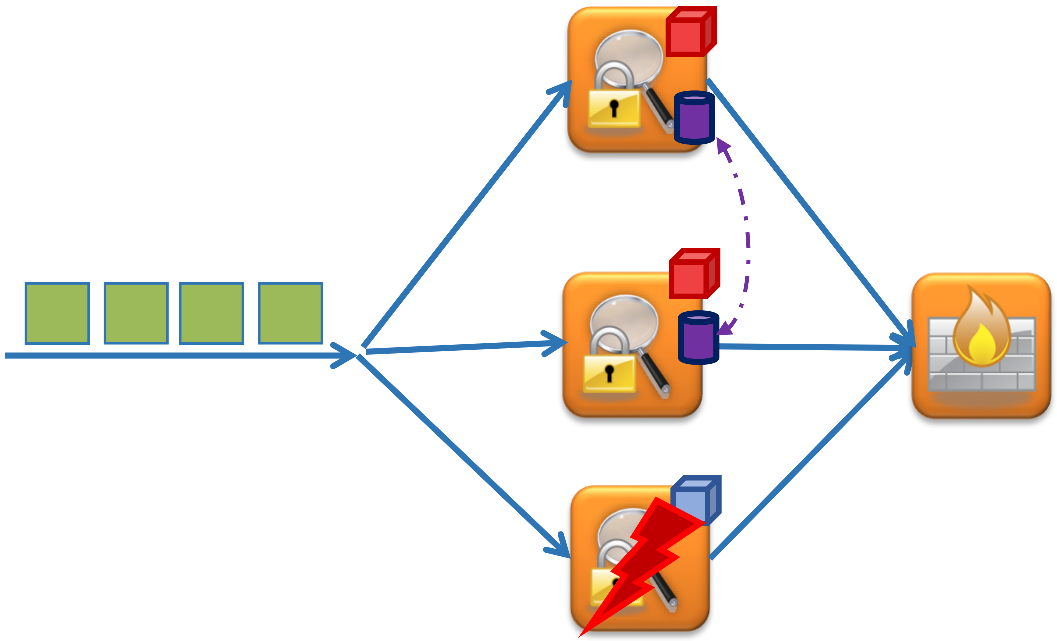

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# Existing Solutions

| Framework | State availability | State transfer | Consistent shared state | Duplicate suppression | Chain-wide ordering |
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| Split/Merge[NSDI'13] | | ✓ | | | |
| OpenNF[SIGCOMM'14] | | ✓ | ✓ | | |
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| S6 [NSDI'18] | | | ✓ | | |
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Incomplete support → restricted functionality

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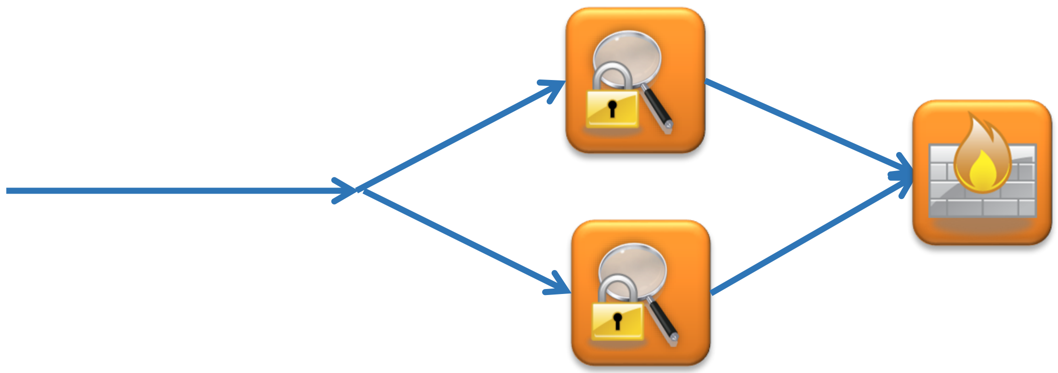

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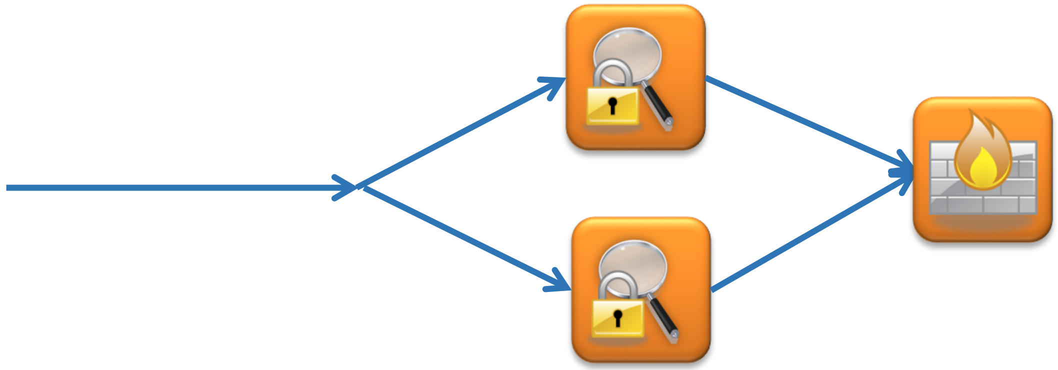

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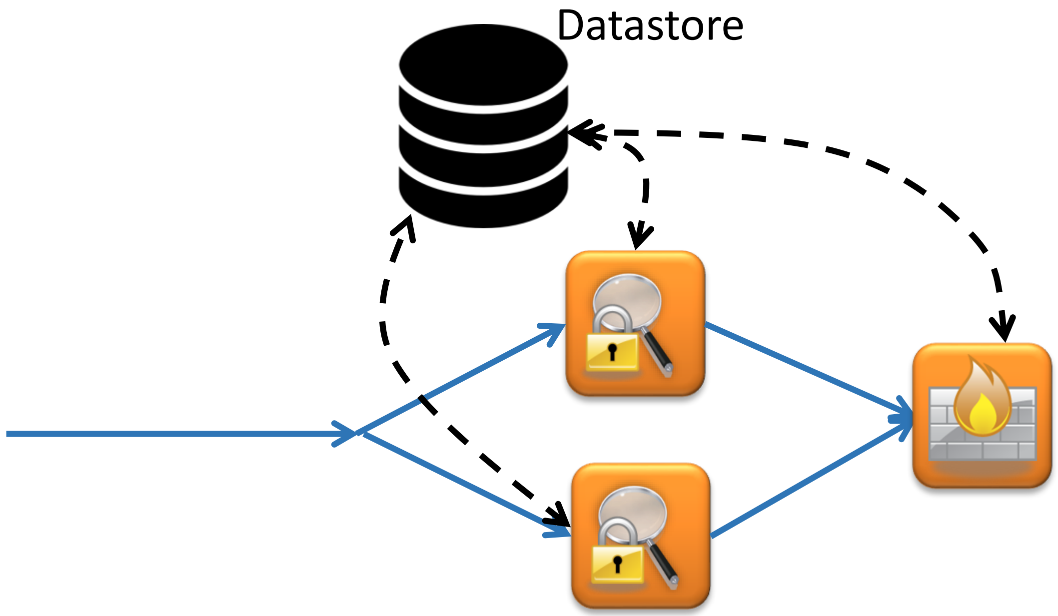

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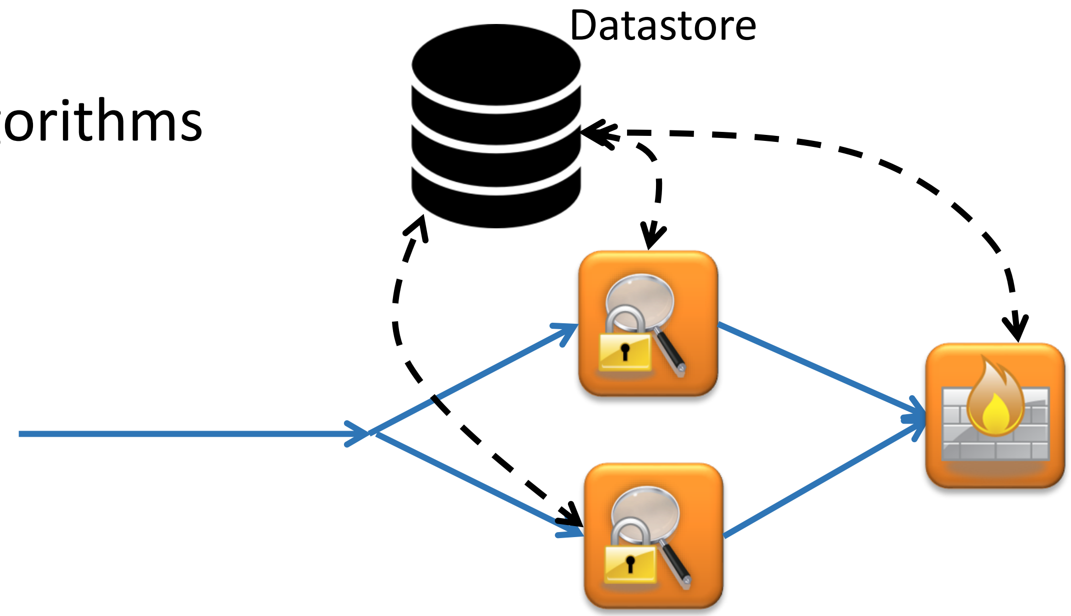

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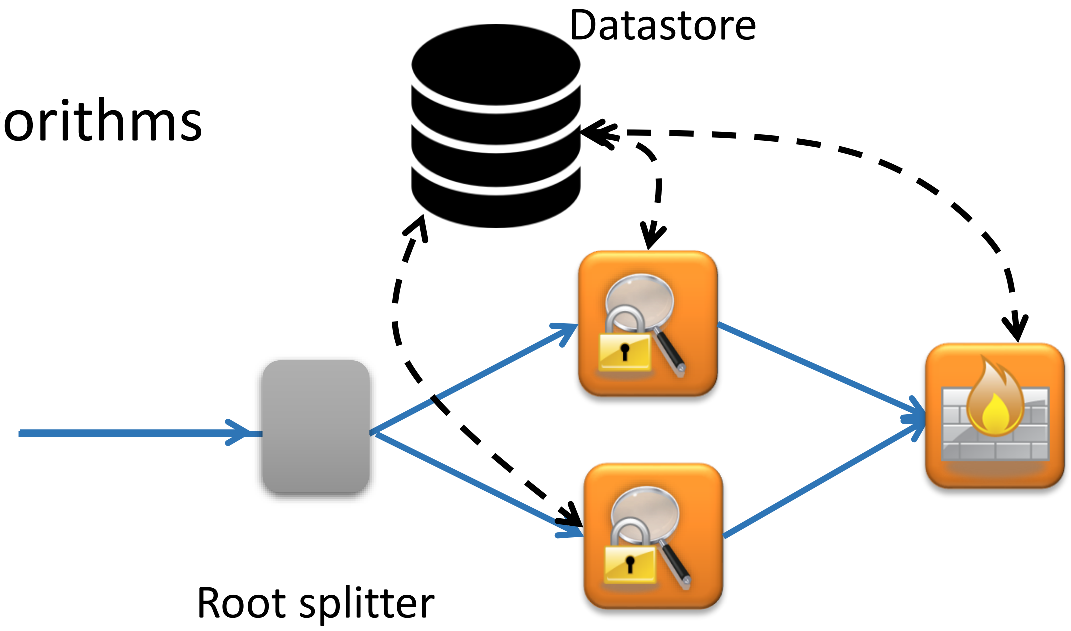

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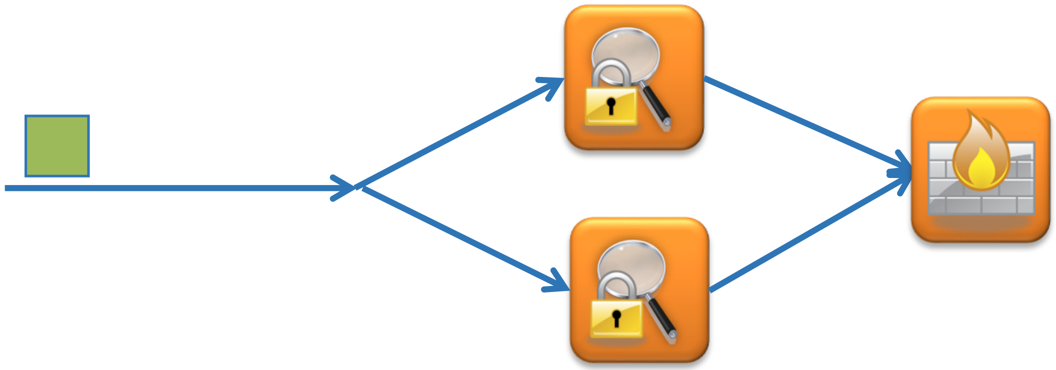

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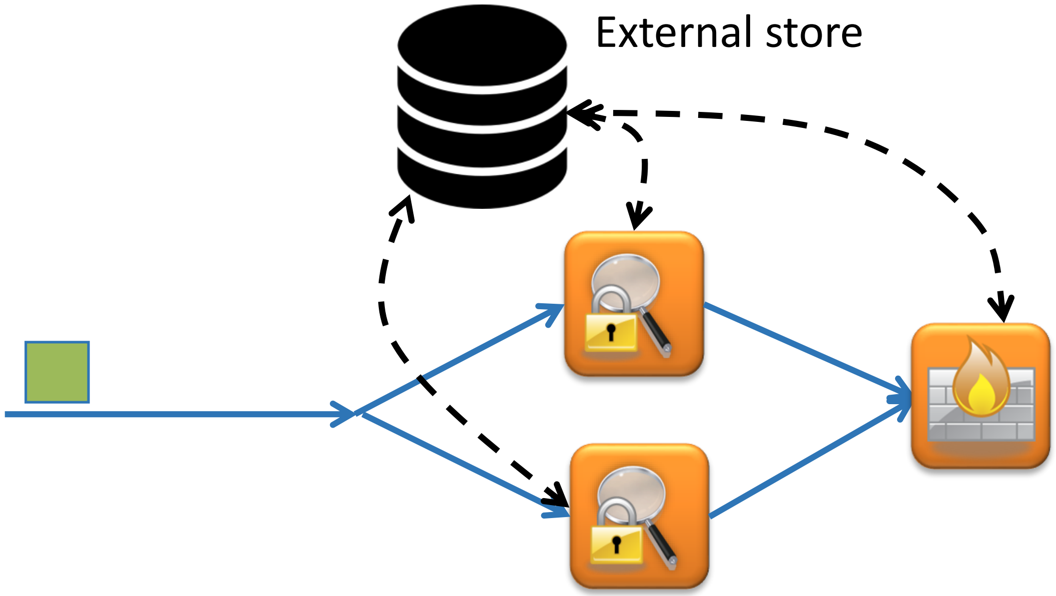

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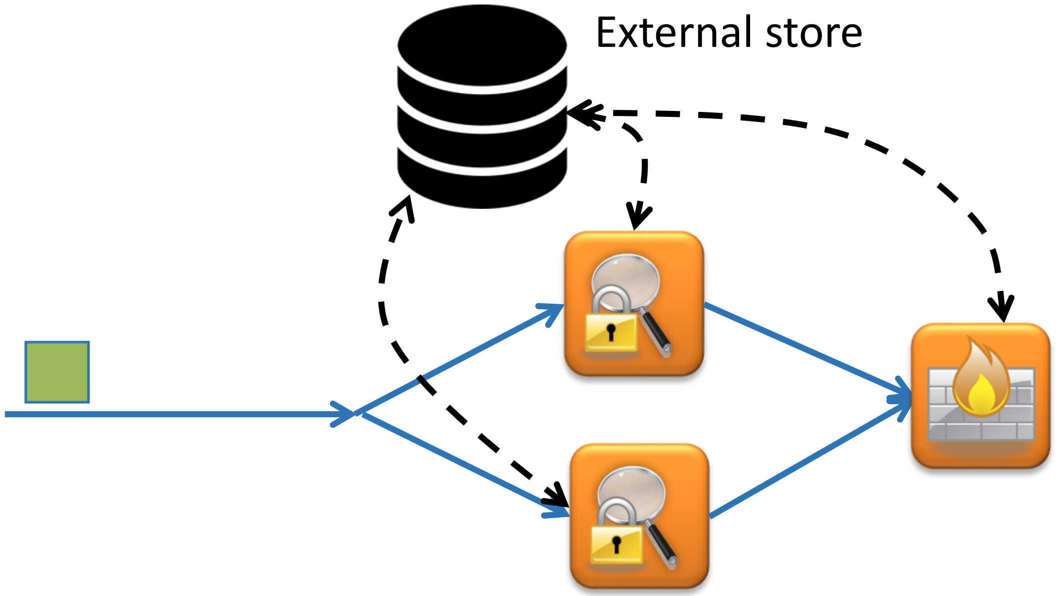


Naively ***externalizing*** the state can ***degrade*** NF performance

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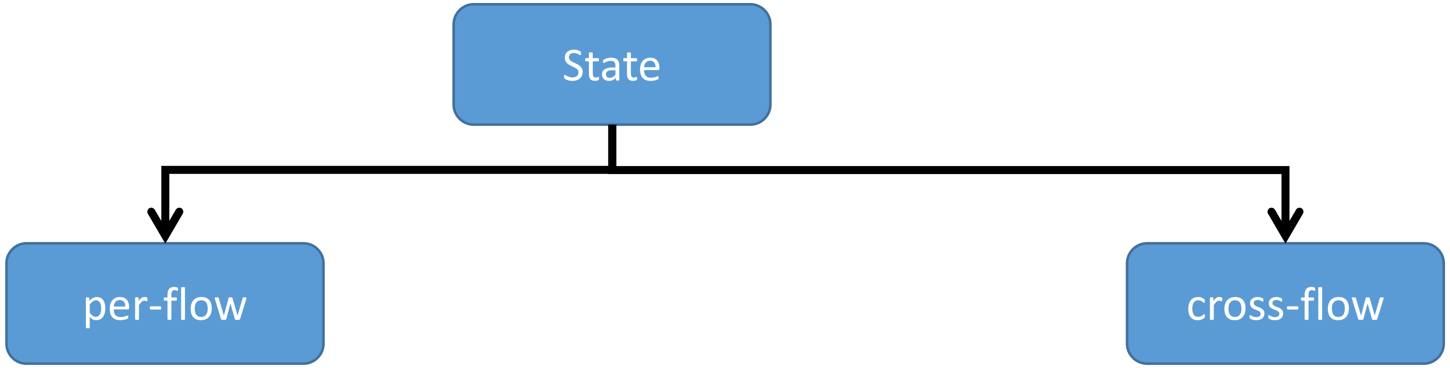

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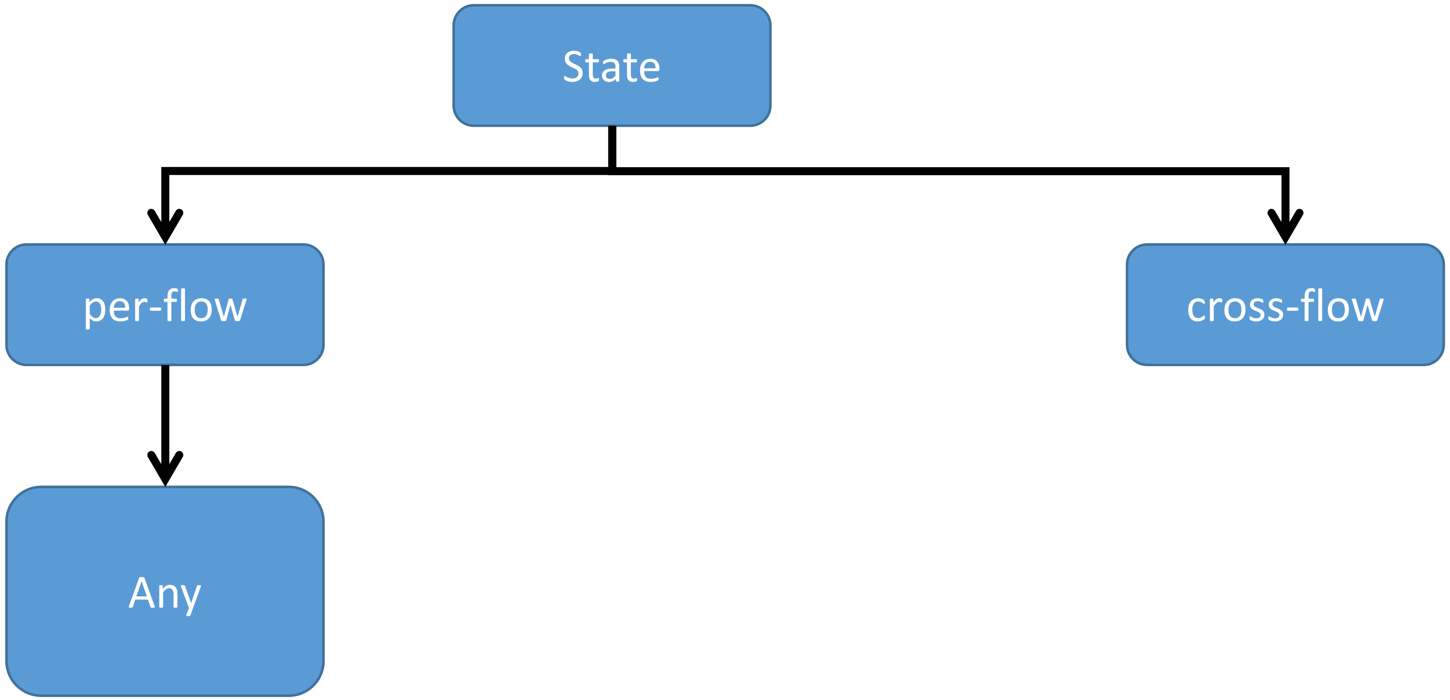


Instance-local caching w/
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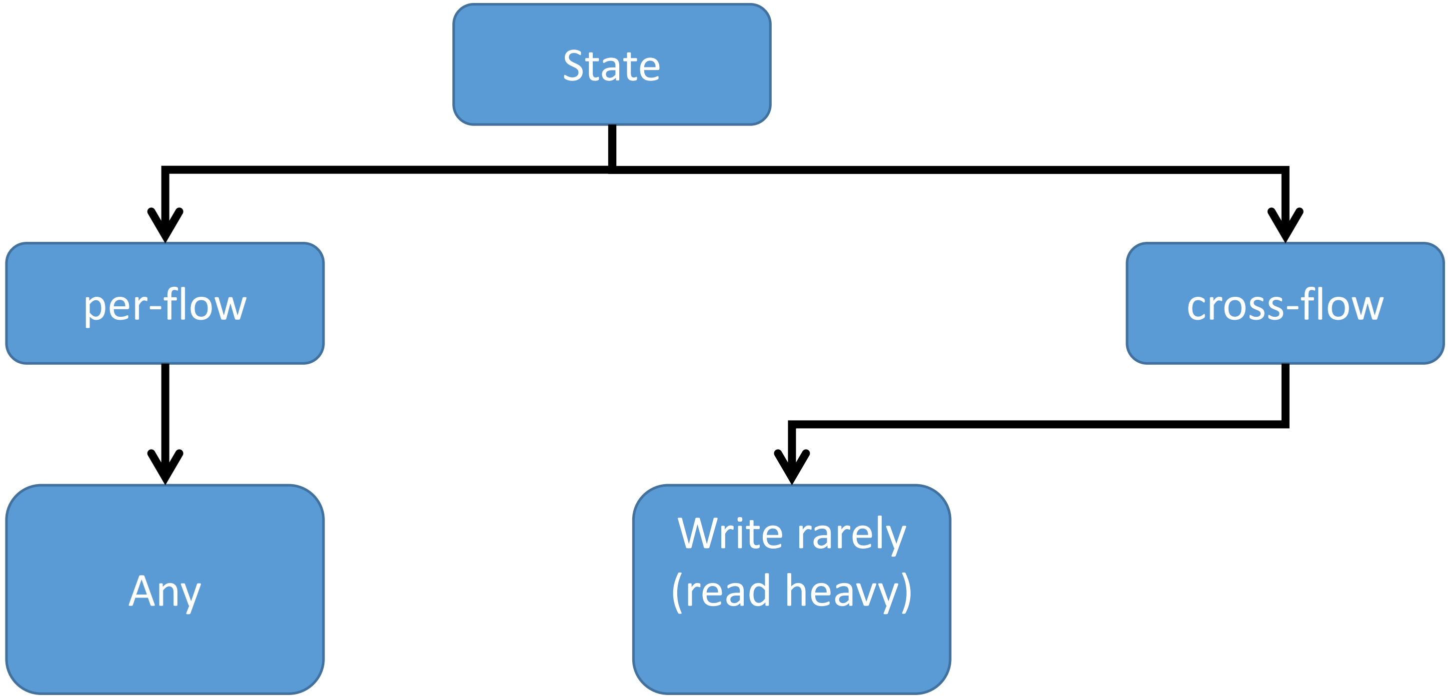


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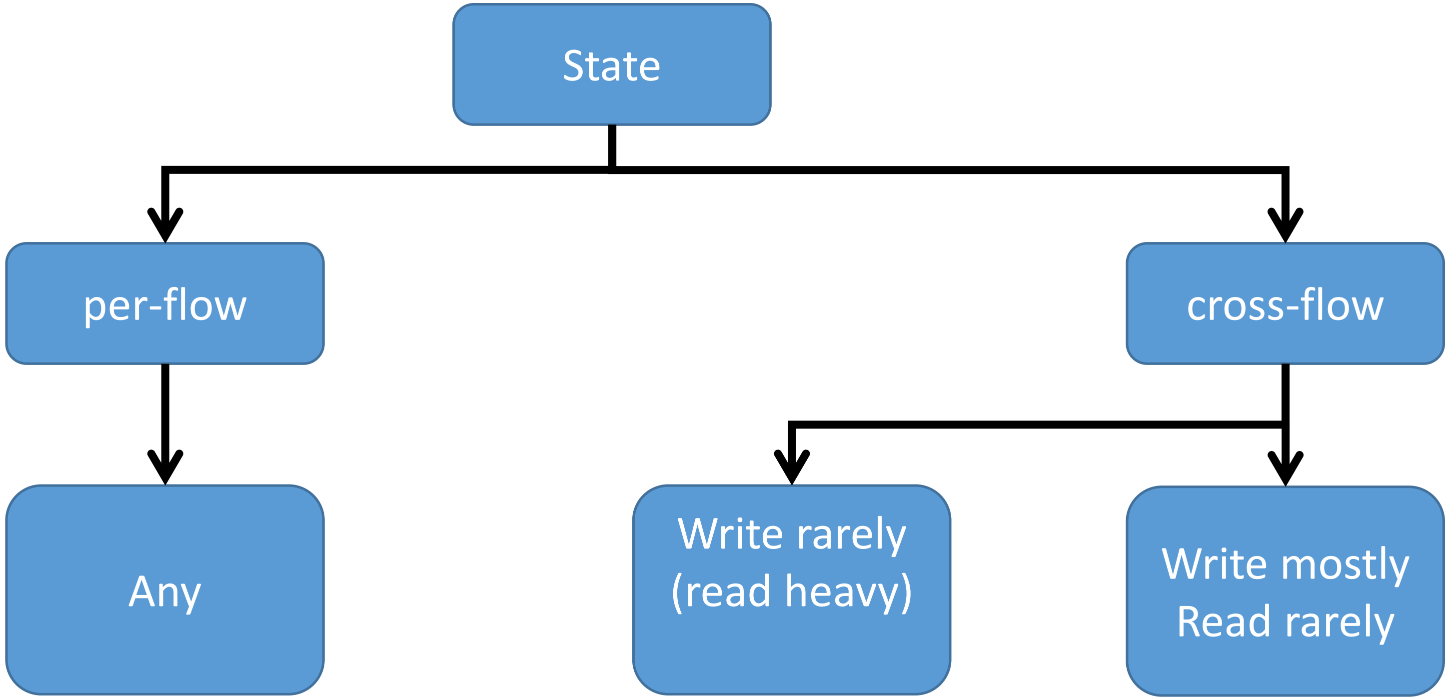


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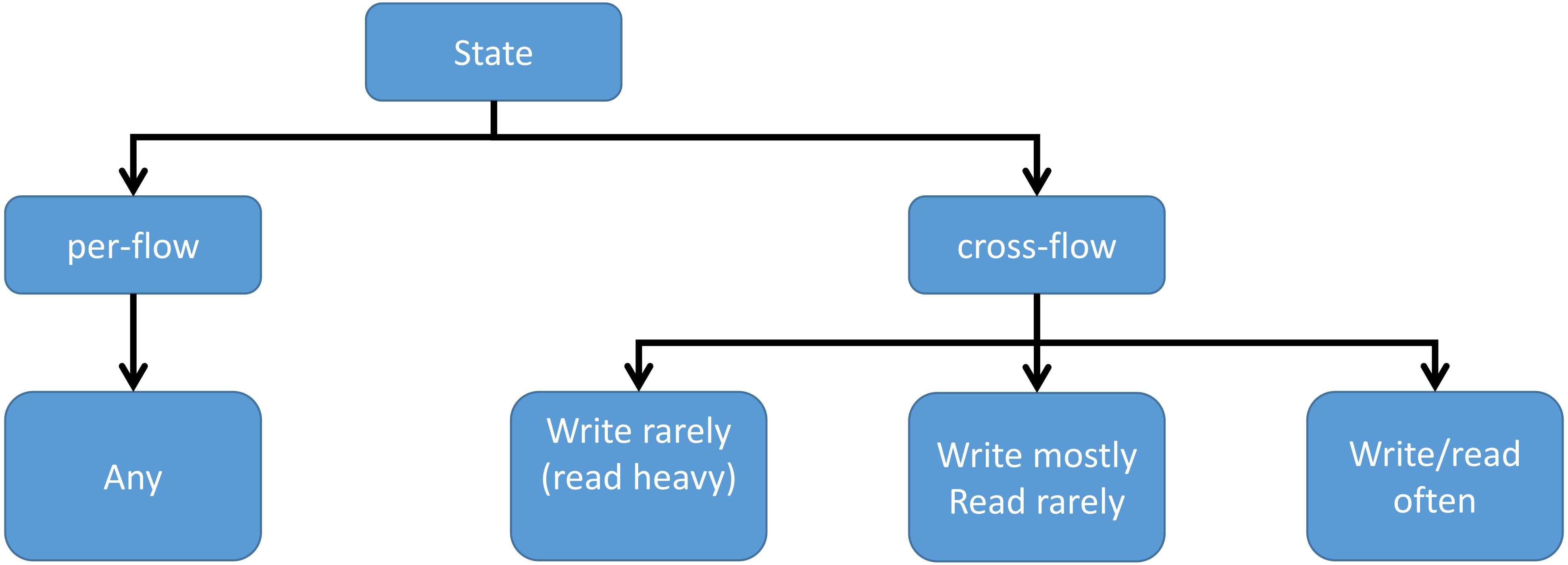


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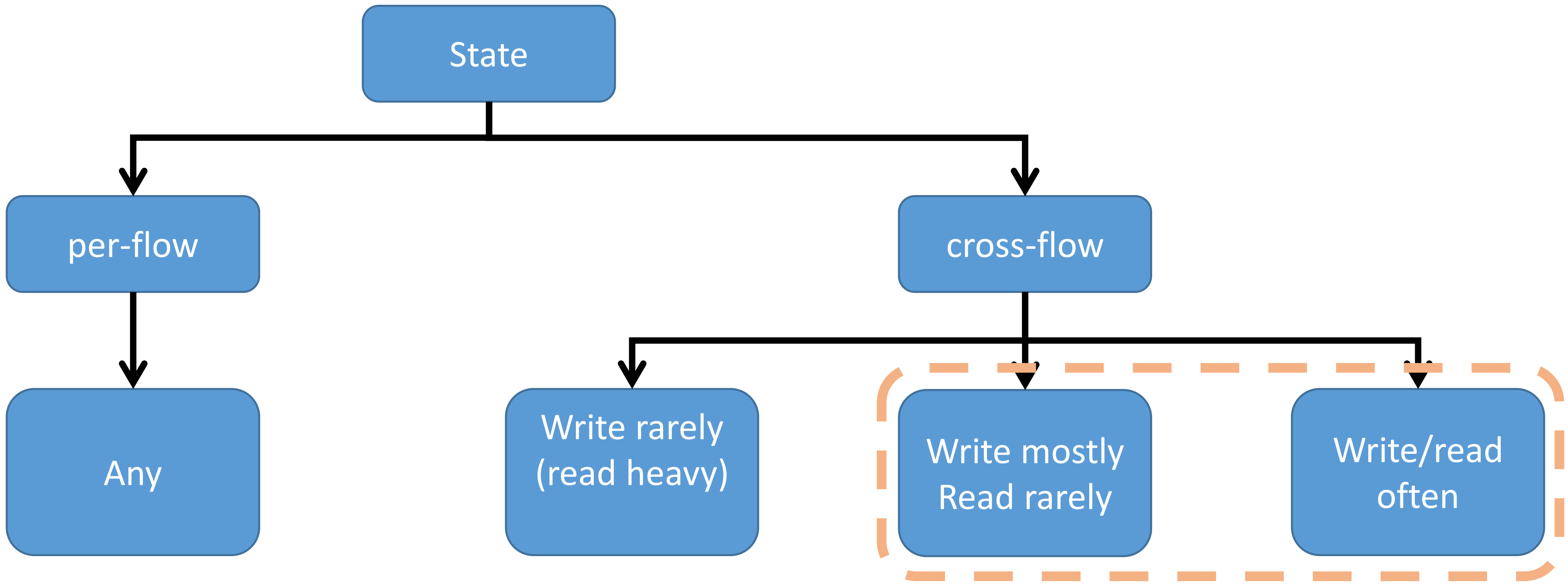


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Operation offloading

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The datastore serializes operations issued by different instances for the same shared state object and applies them in the background

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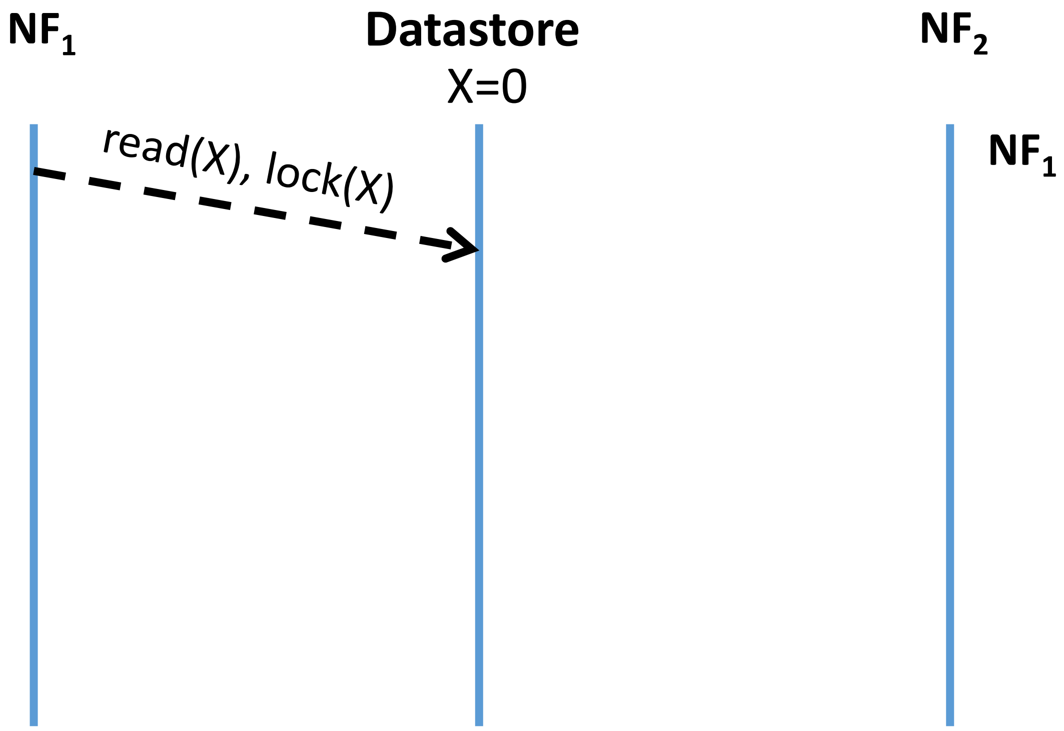

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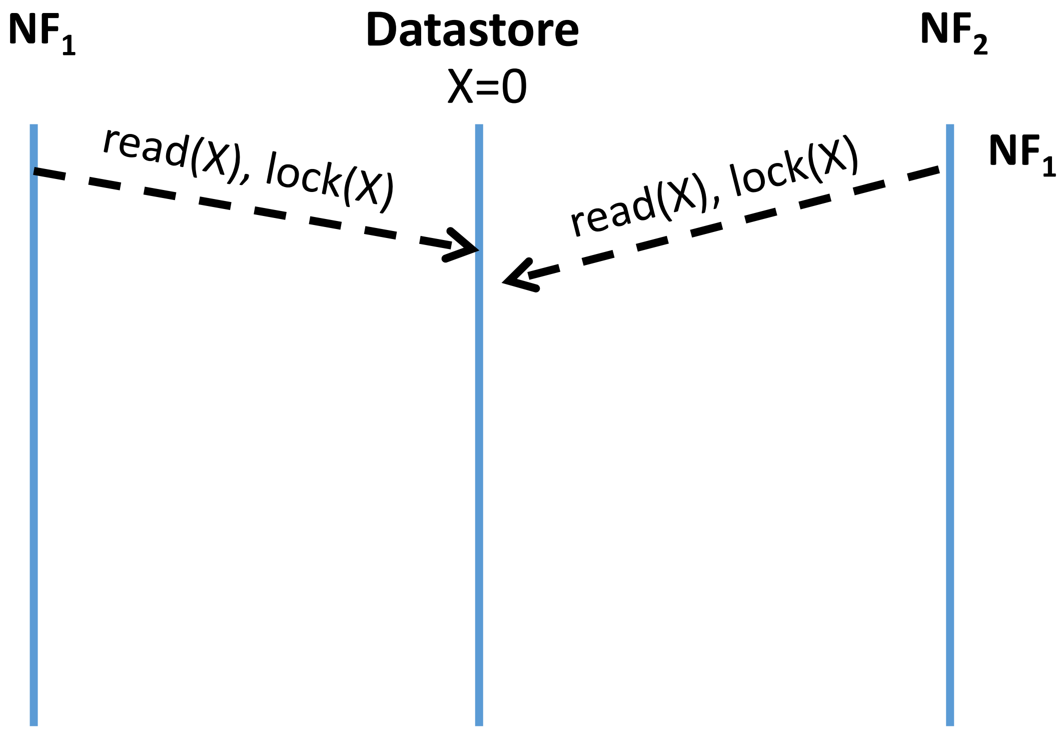

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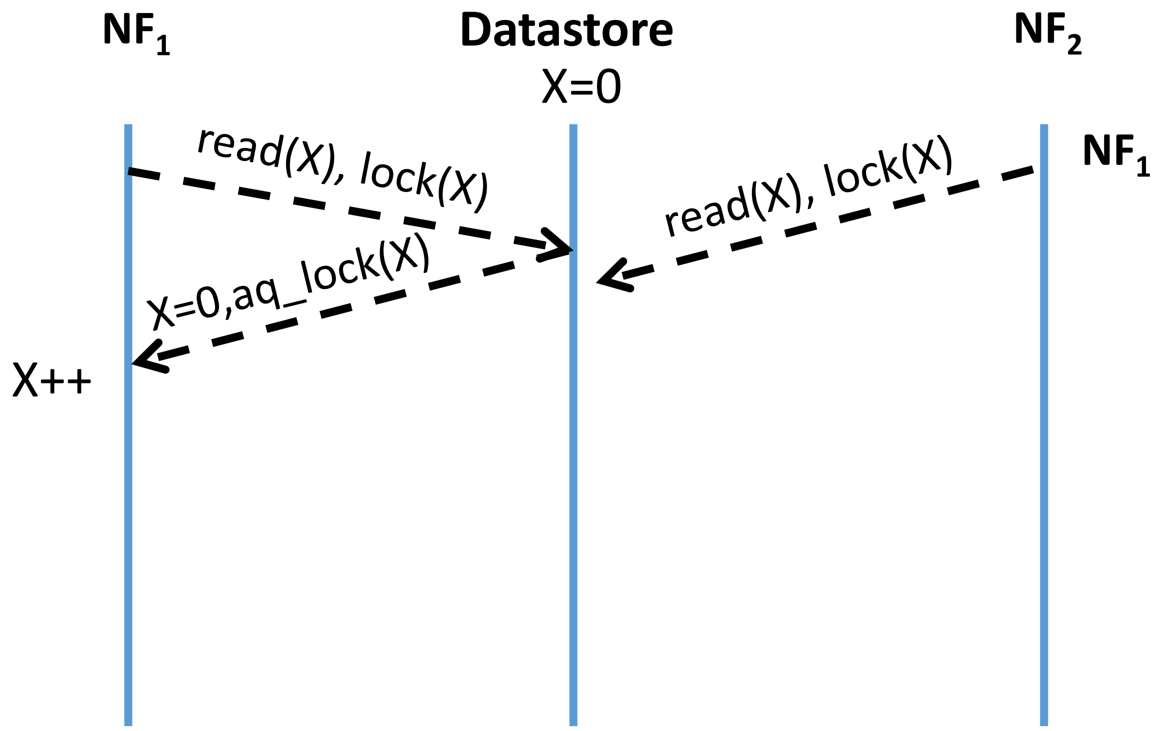

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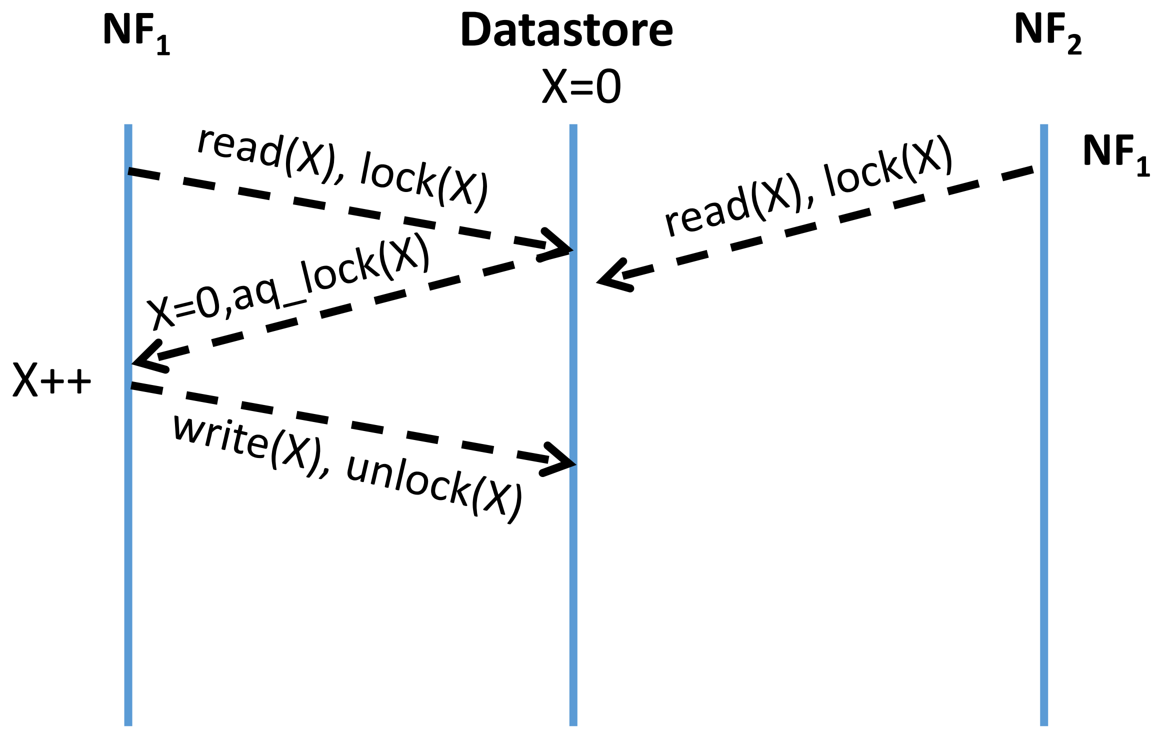

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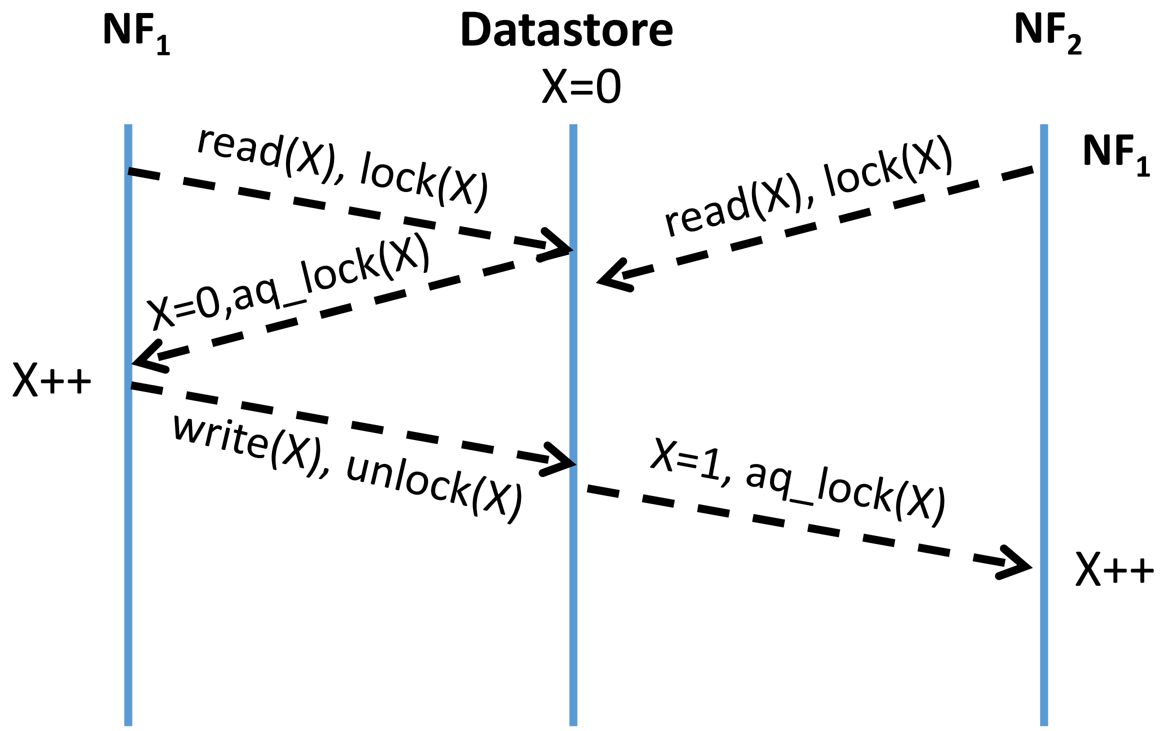

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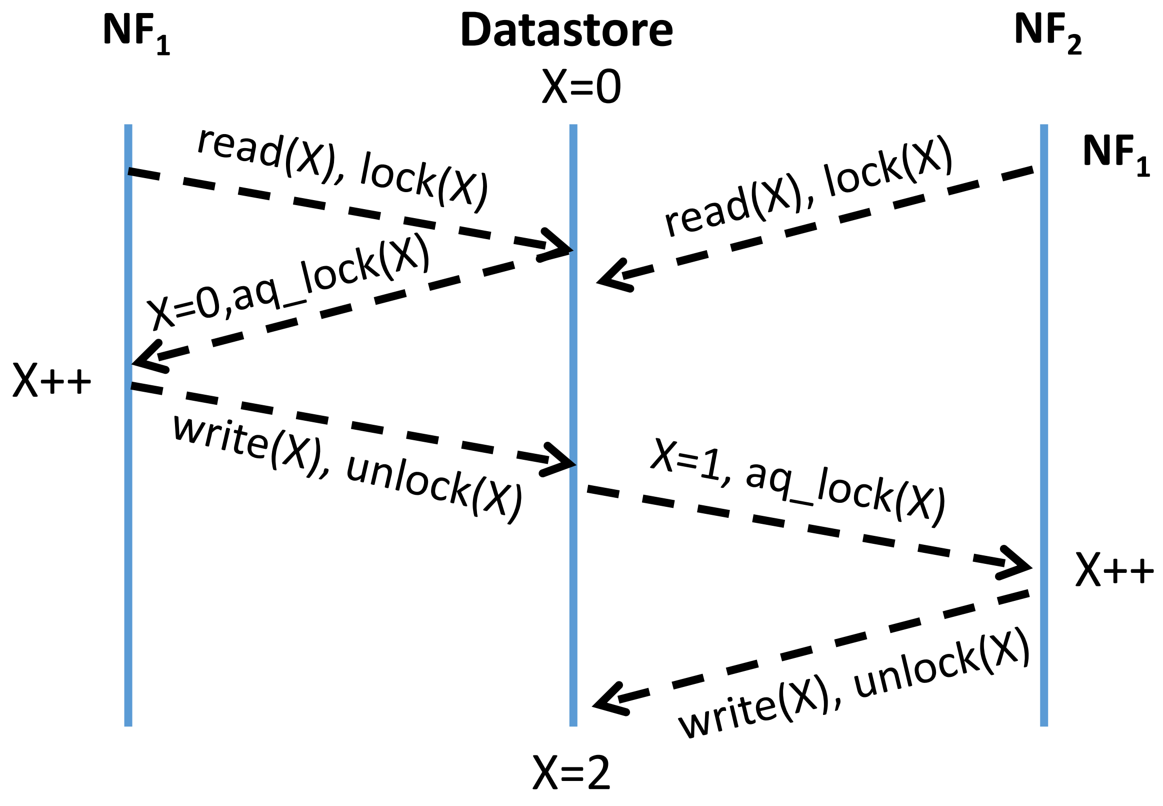

# State Maintenance - Offloading Operation

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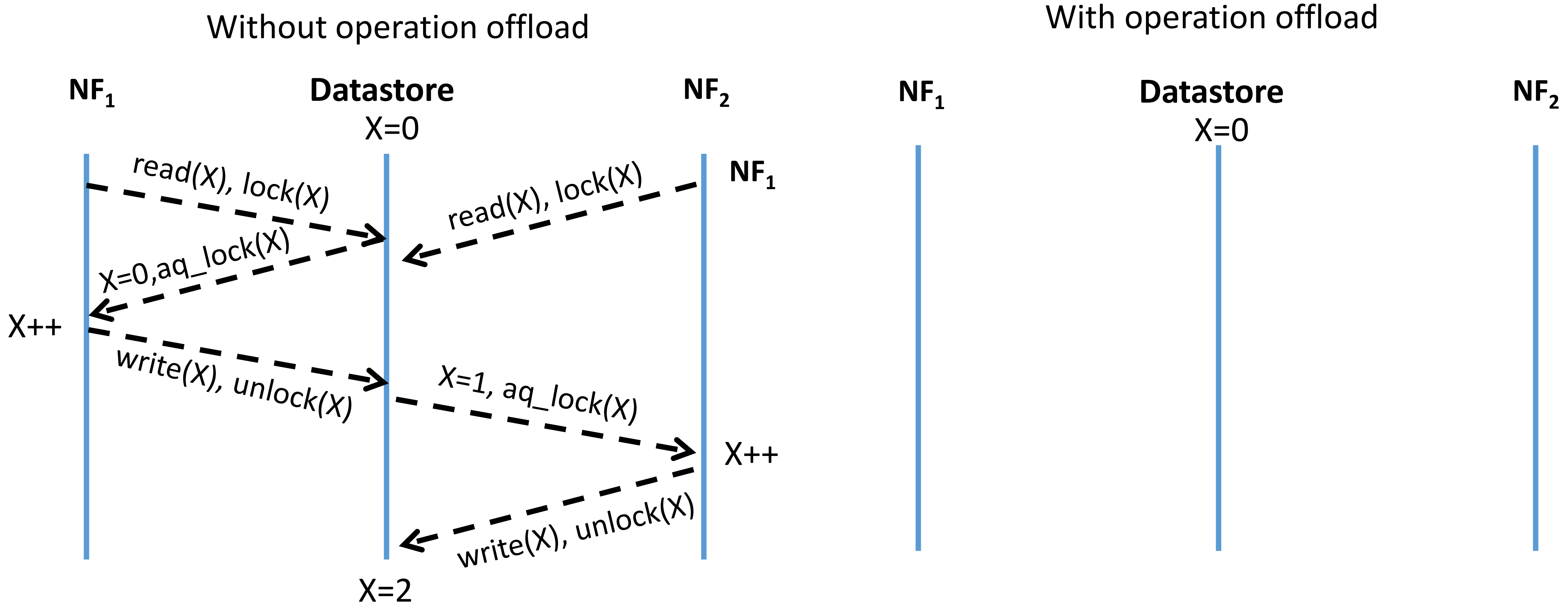

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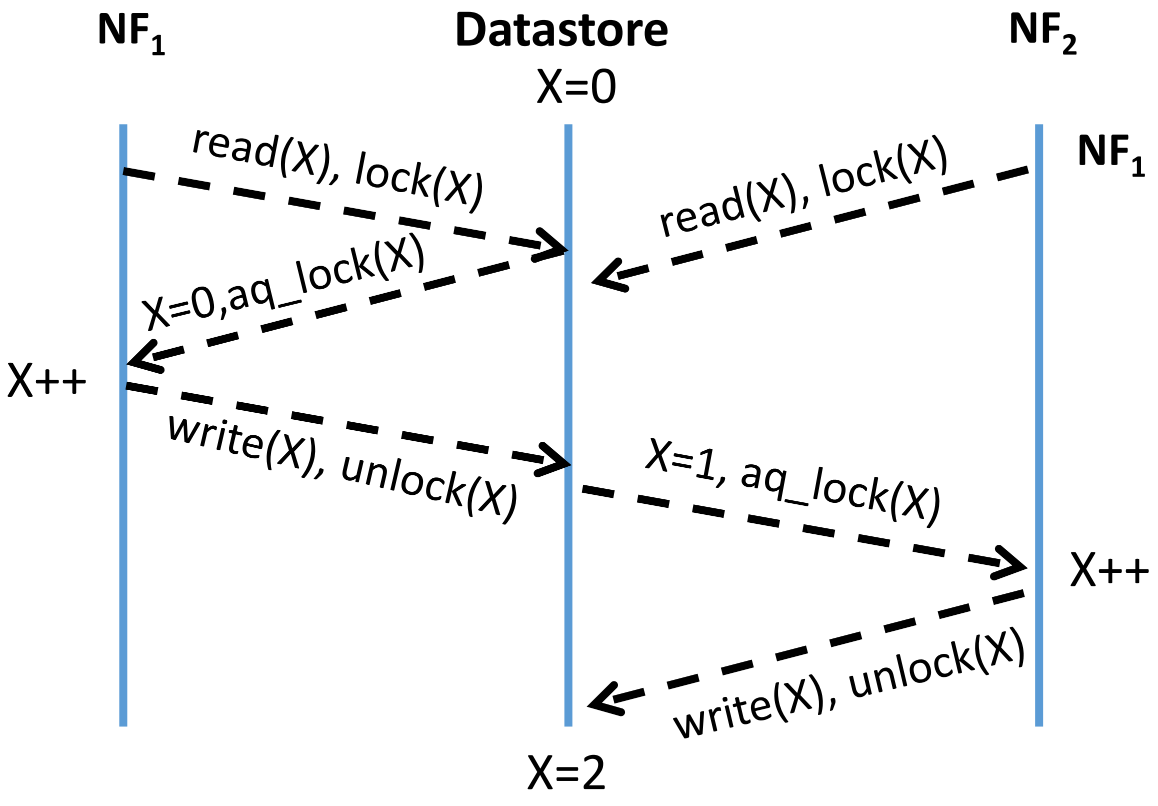
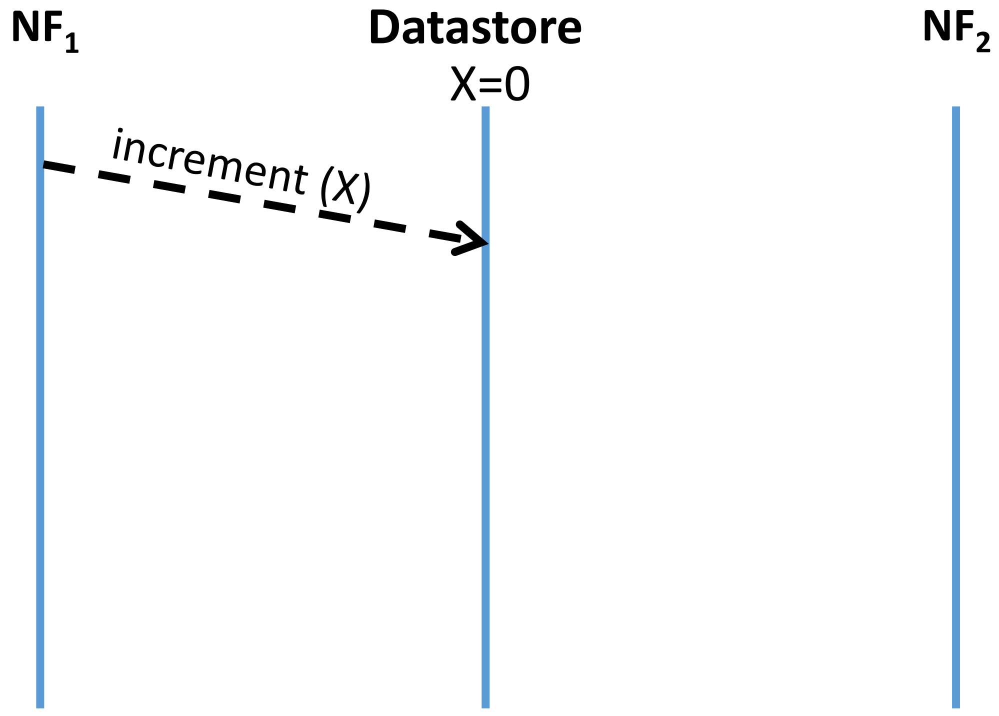



With operation offload



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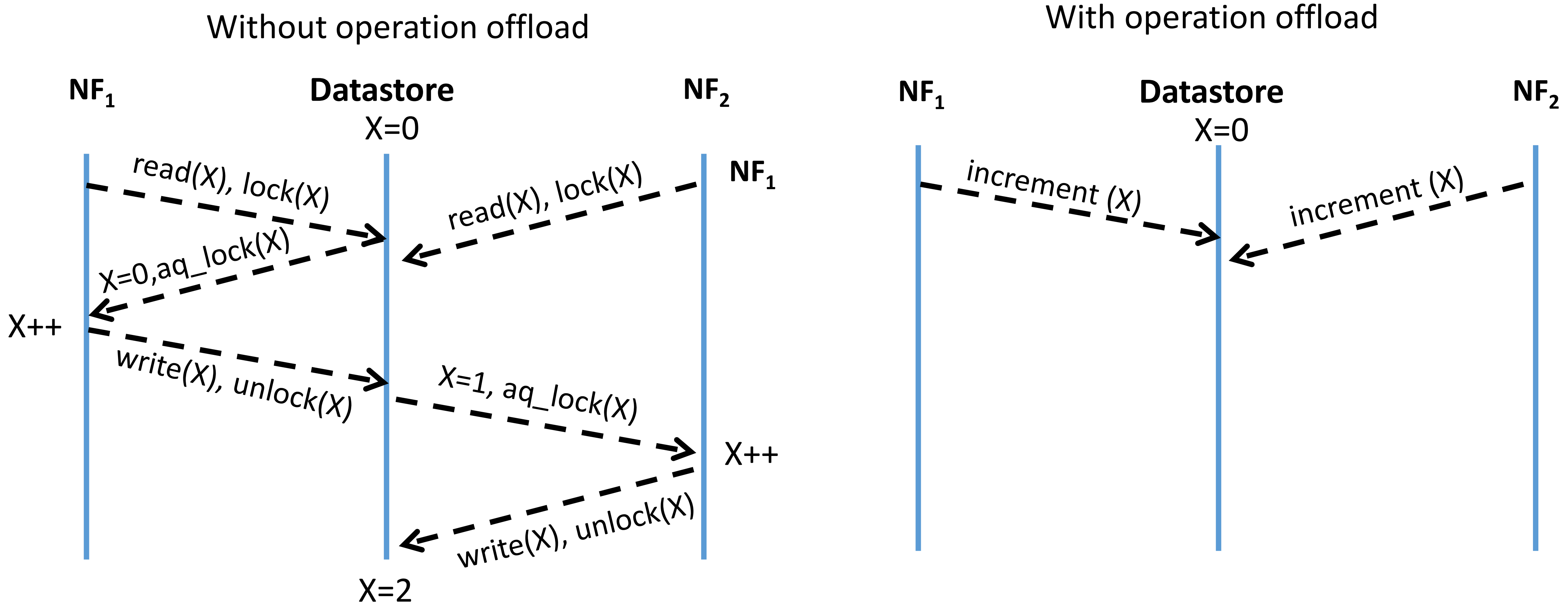

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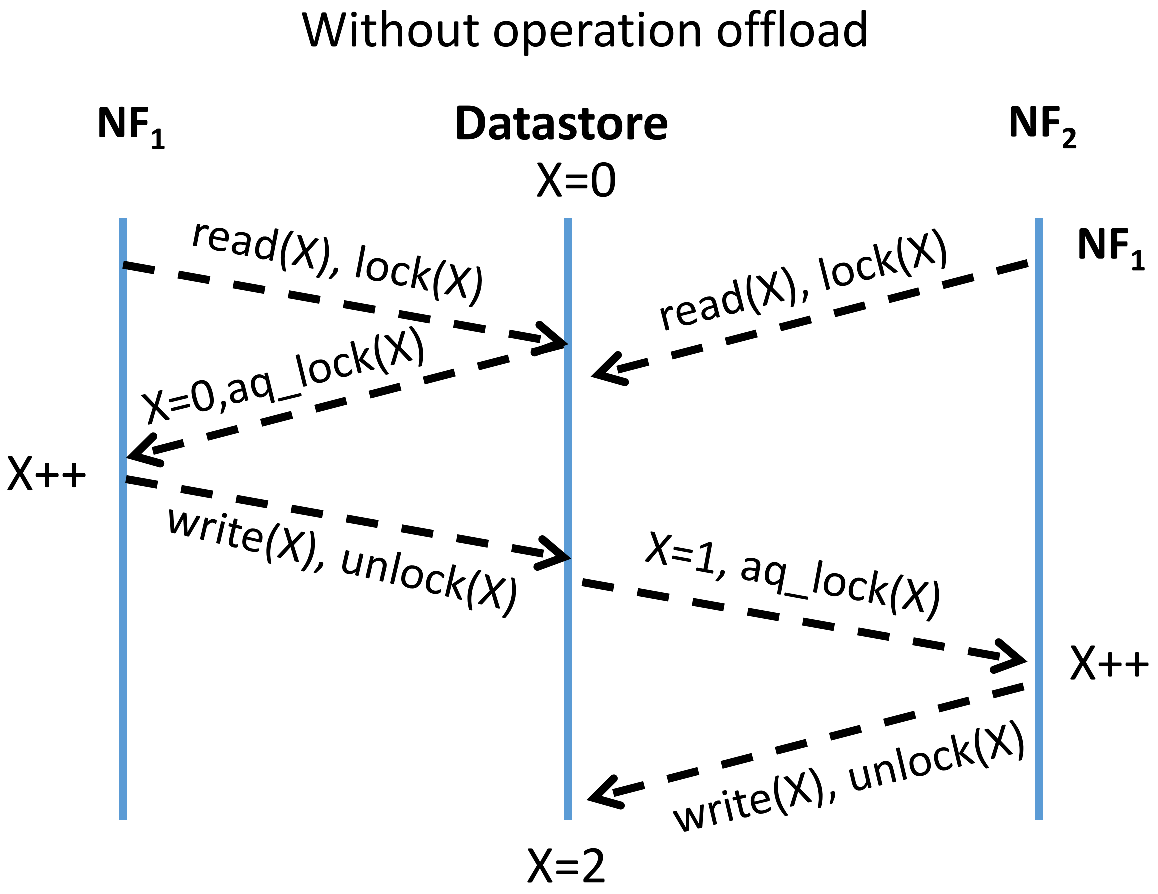


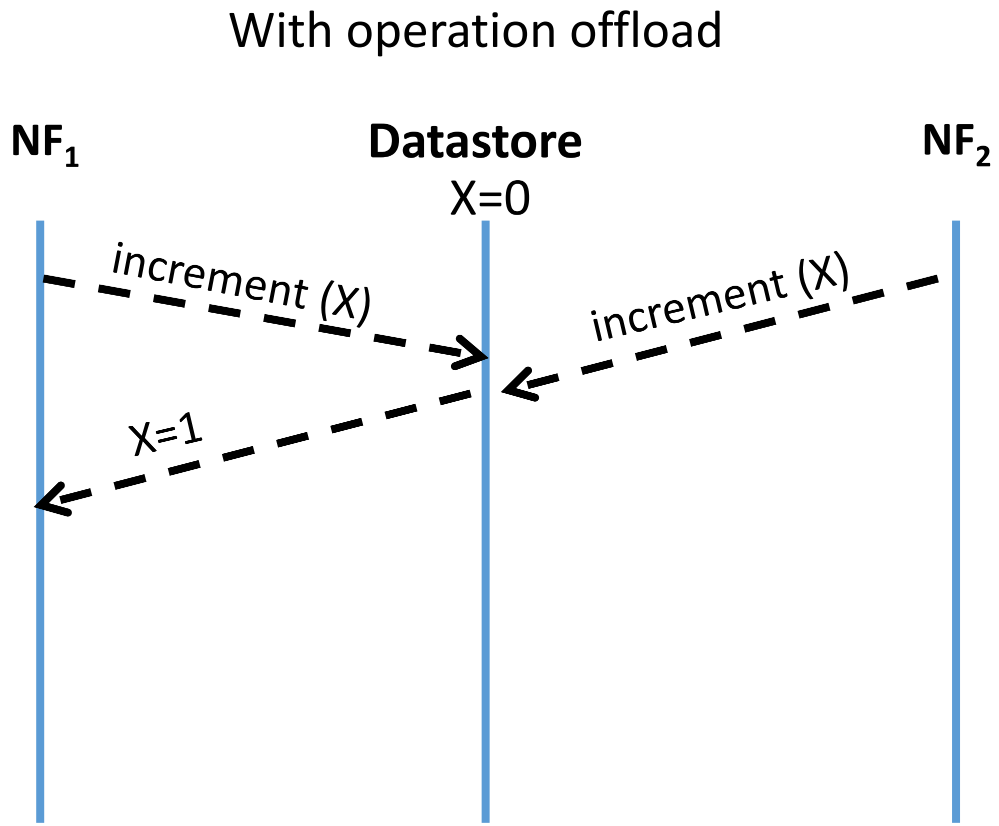

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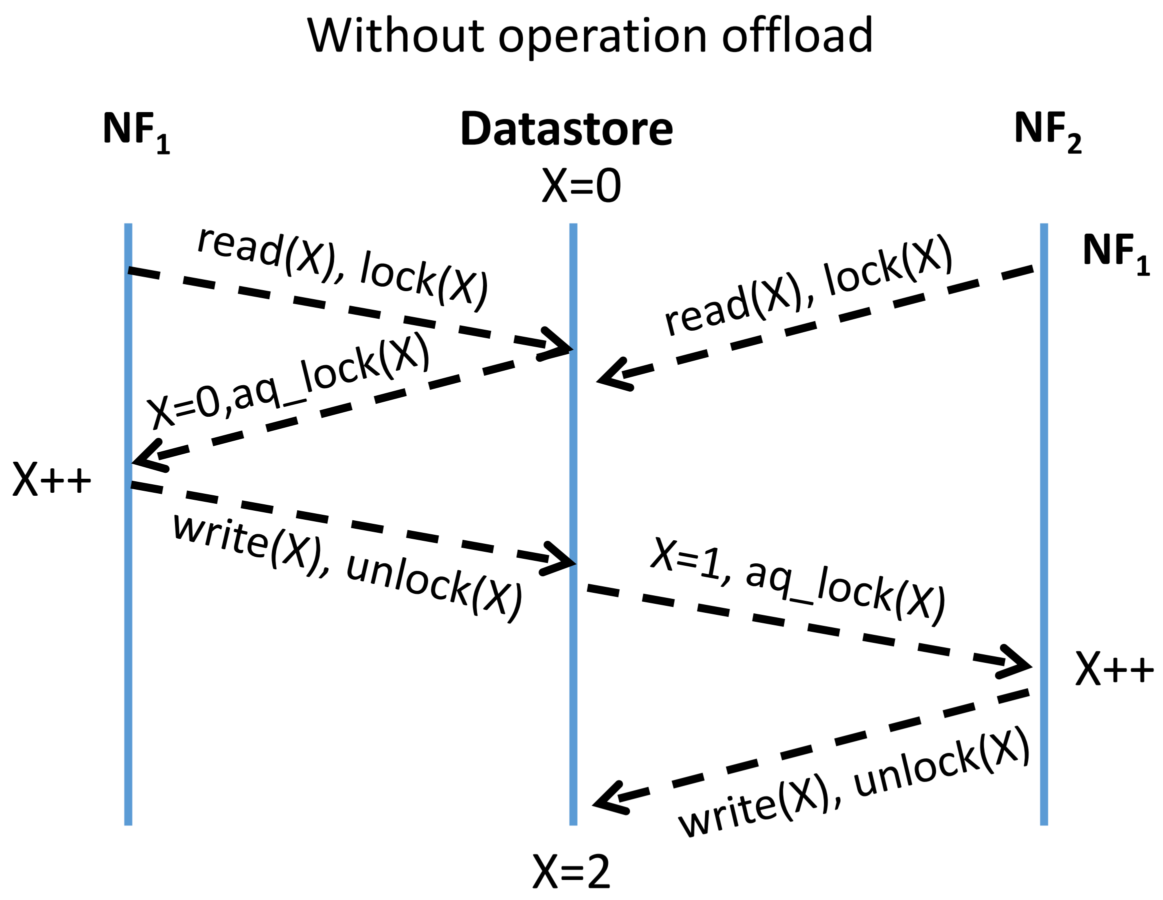
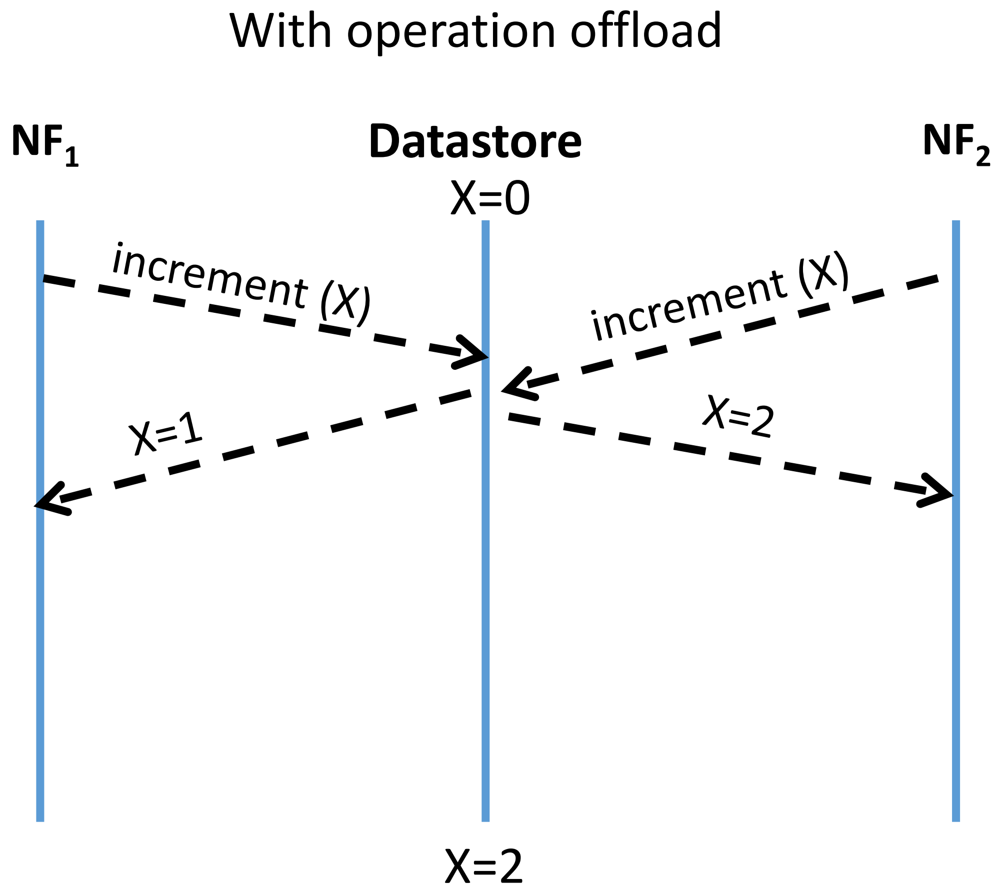
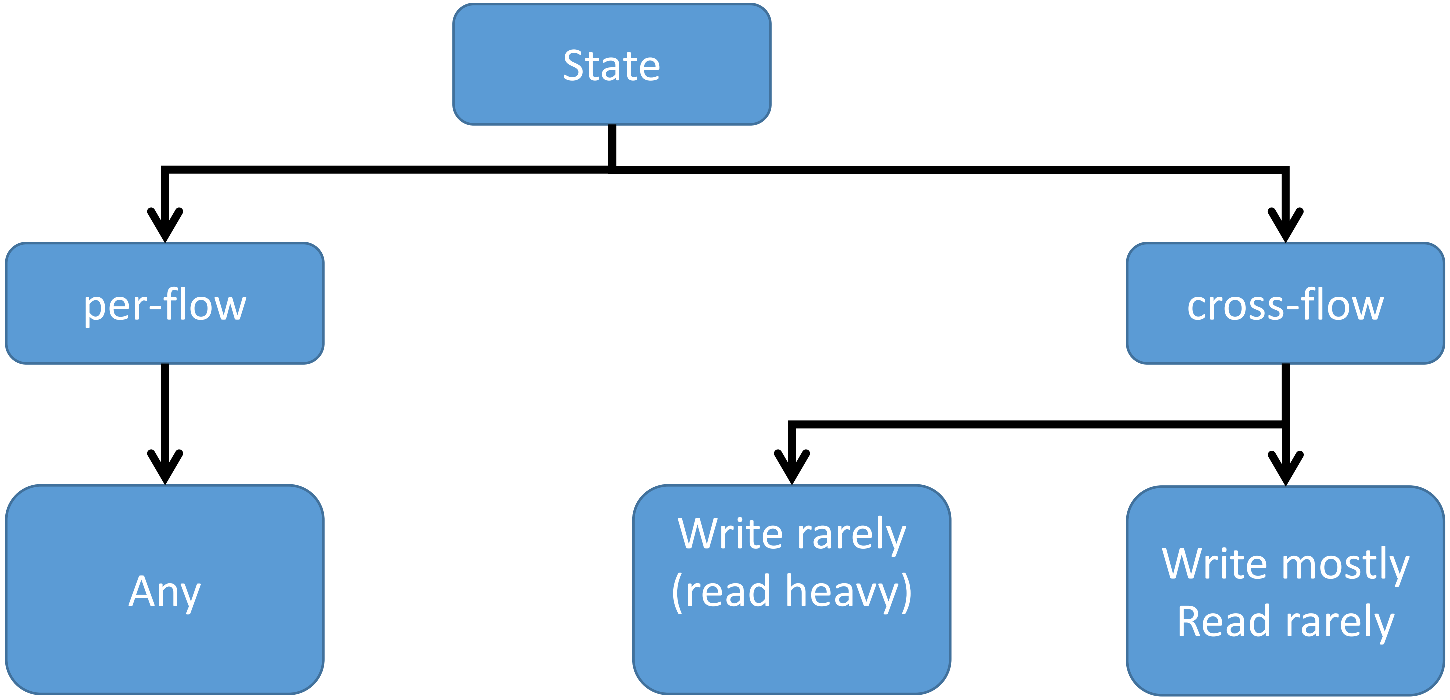


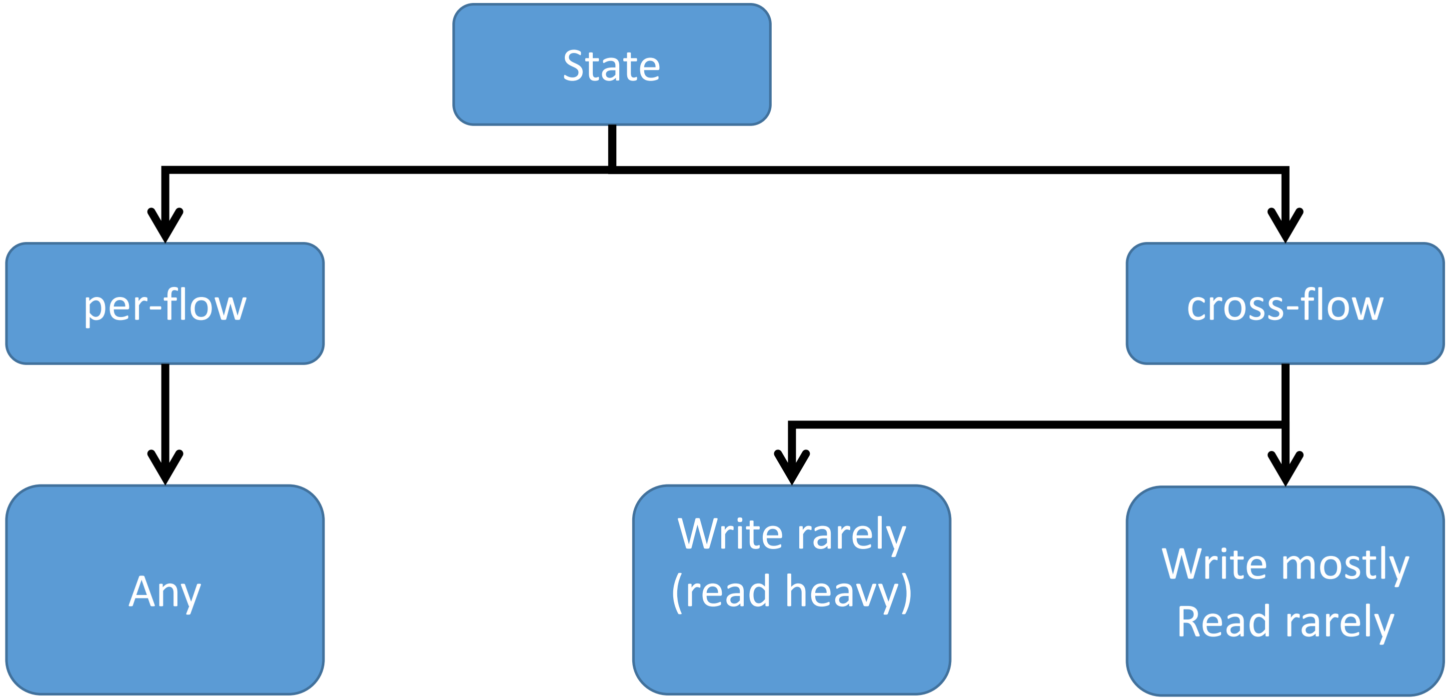
# State Management Strategies




Instance-local caching w/ periodic nonblocking flush

Instance-local caching w/ callbacks

# State Management Strategies

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Non-blocking operation without caching

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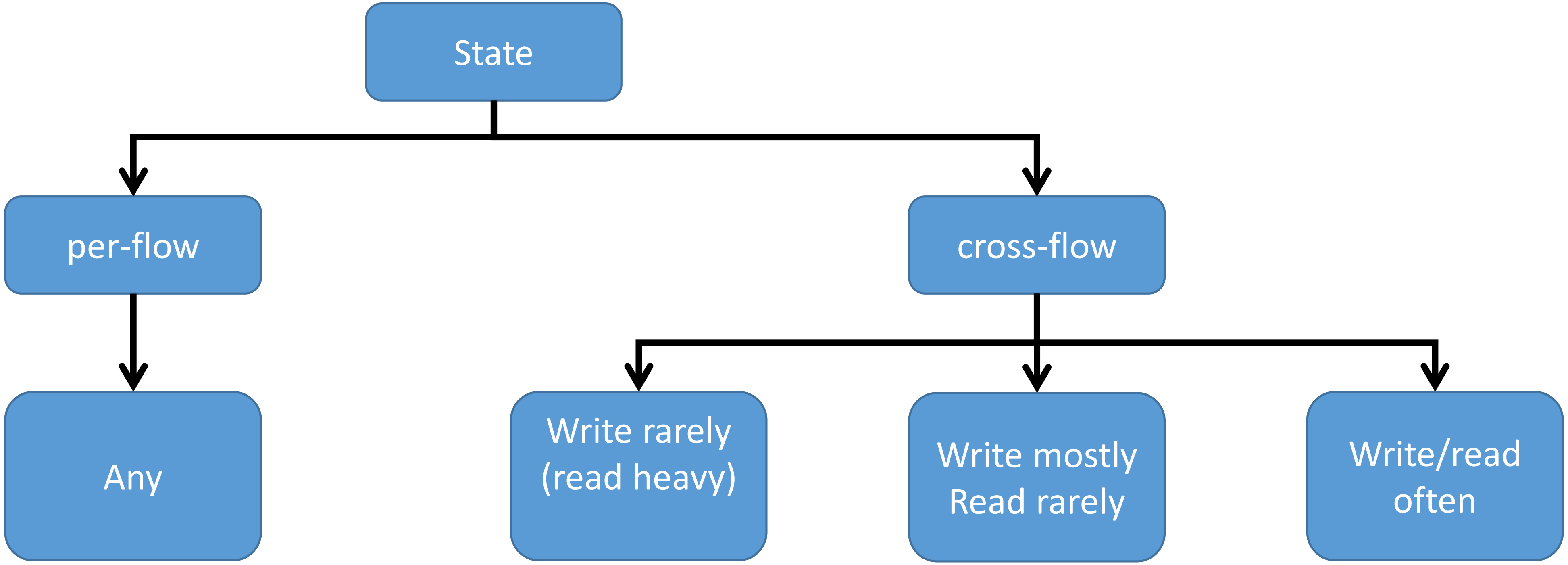



Instance-local caching w/ periodic nonblocking flush

Instance-local caching w/ callbacks

Non-blocking operation without caching

Depends upon traffic split. Cache, if split allows; flush periodically

# CHC

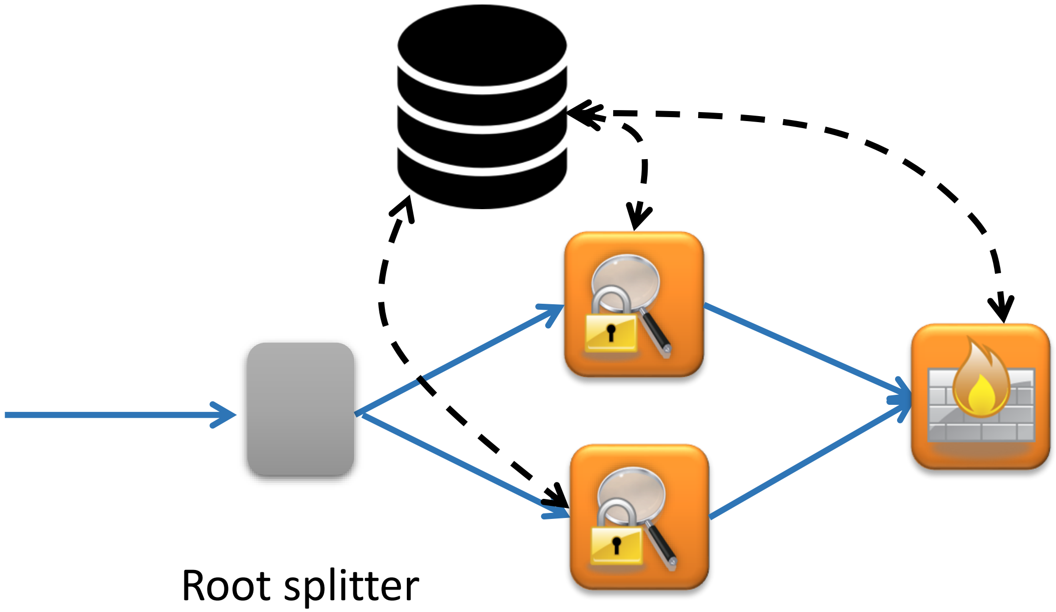
CHC is a generic NFV framework to support all of these requirements without trading off ***correctness*** for ***performance*** or ***functionality***

CHC consist of three main  building blocks

1. State store external to NF
2. NF state-aware state management algorithms
3. Metadata – logical clock and logs

# Metadata

CHC adds a “root splitter” at the entry of a chain that:

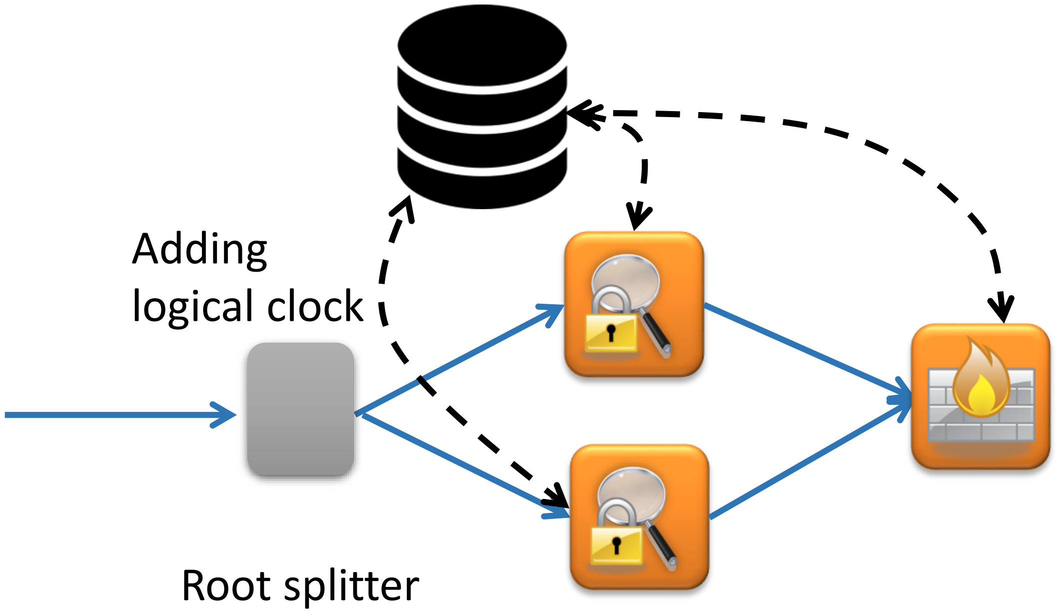


Root splitter

# Metadata

CHC adds a "root splitter" at the entry of a chain that:

- Root splitter attaches a unique logical clock with each packet. Logical clock is used for ***duplication suppression, ordering,*** and ***traffic replay***



# Metadata

CHC adds a "root splitter" at the entry of a chain that:

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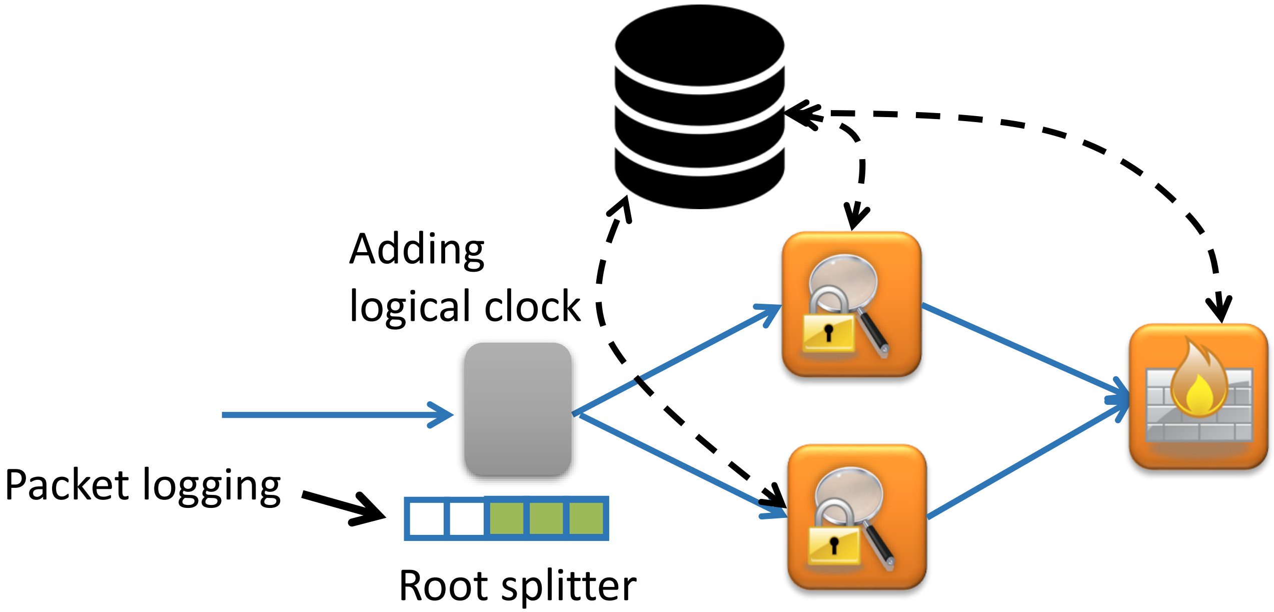

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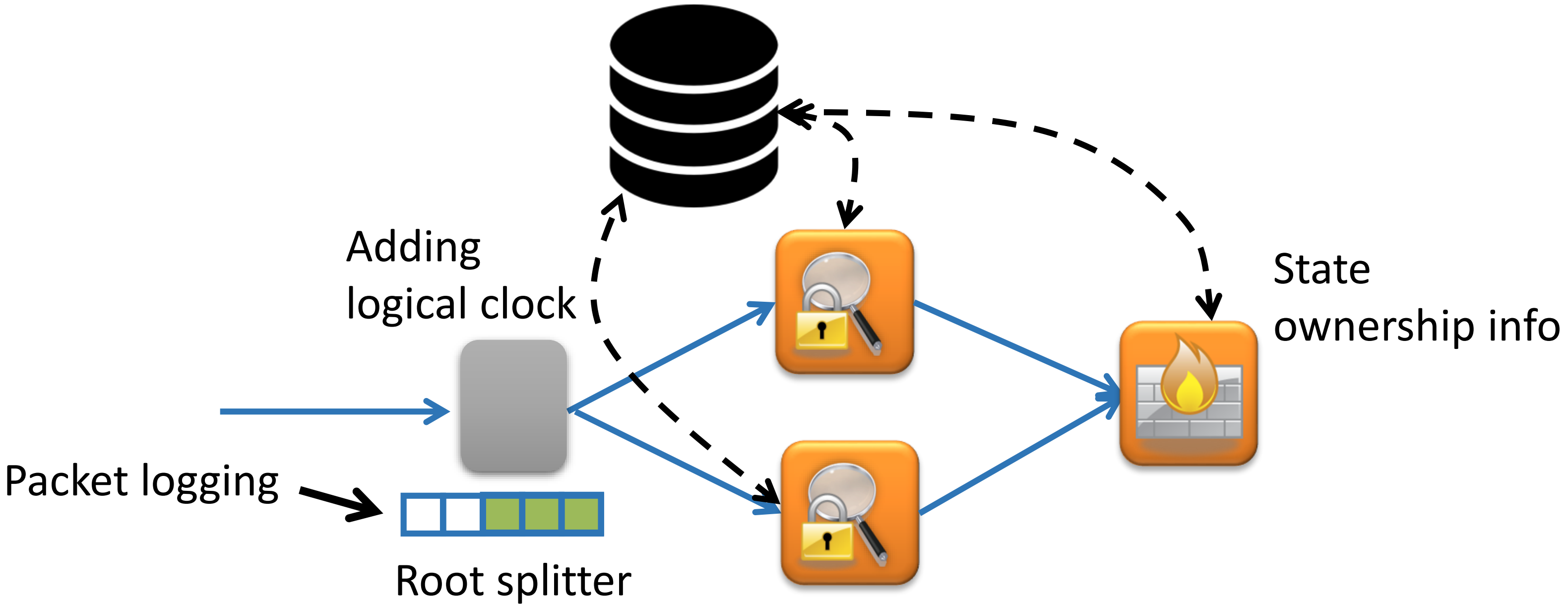
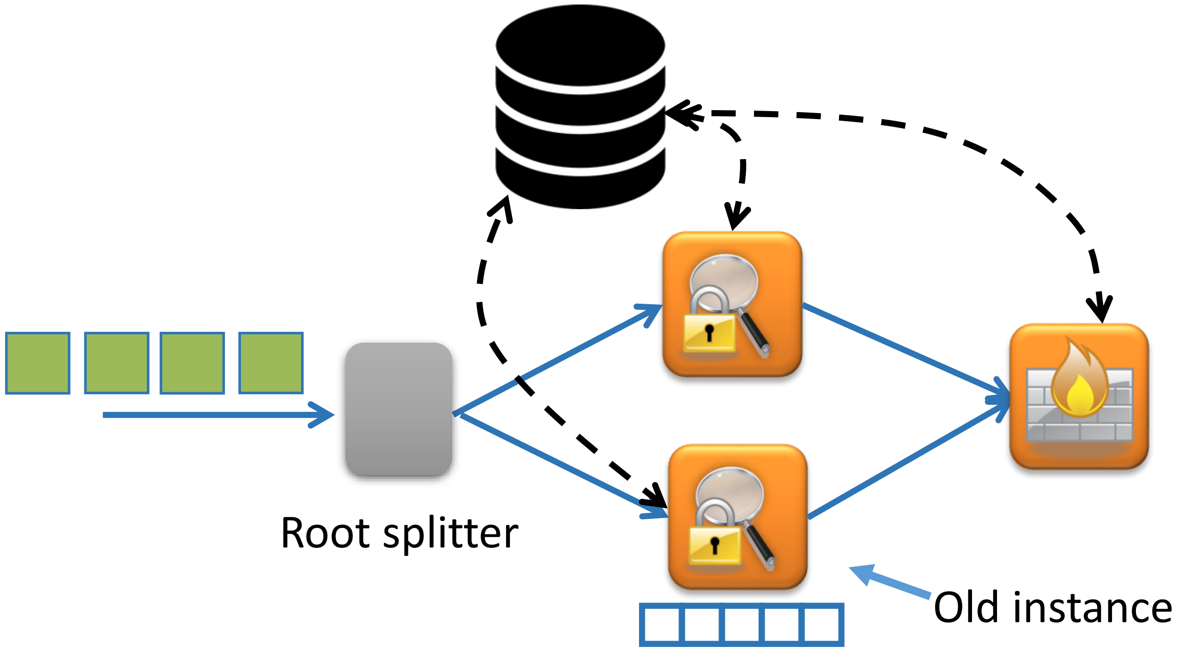
CHC encodes state object’s ownership information and logical clock associated with state operations as metadata

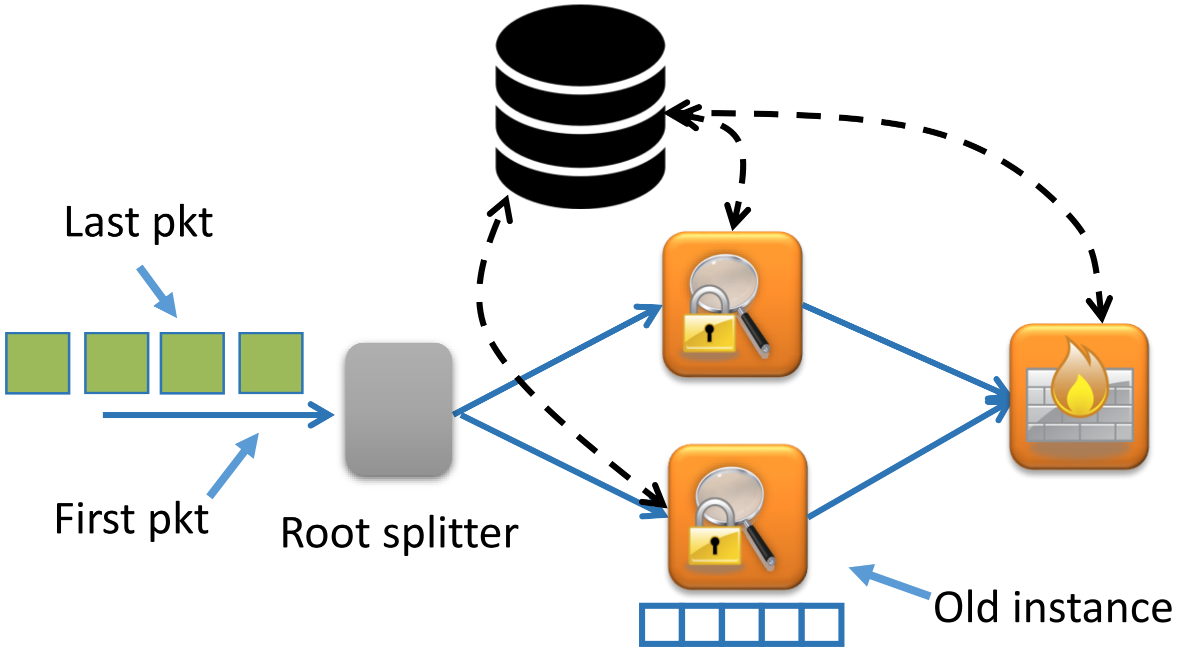


# CHC – Elastic Scaling



# CHC – Elastic Scaling

- CHC marks the last packet going to the old instance and first packet going to the new instance



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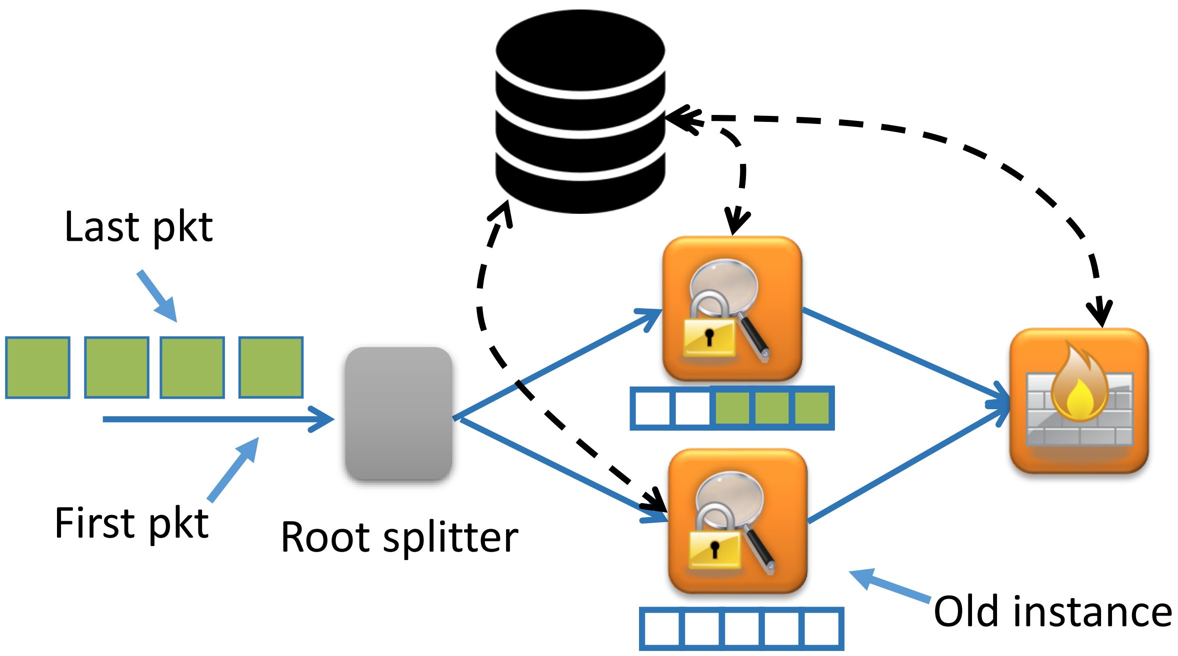
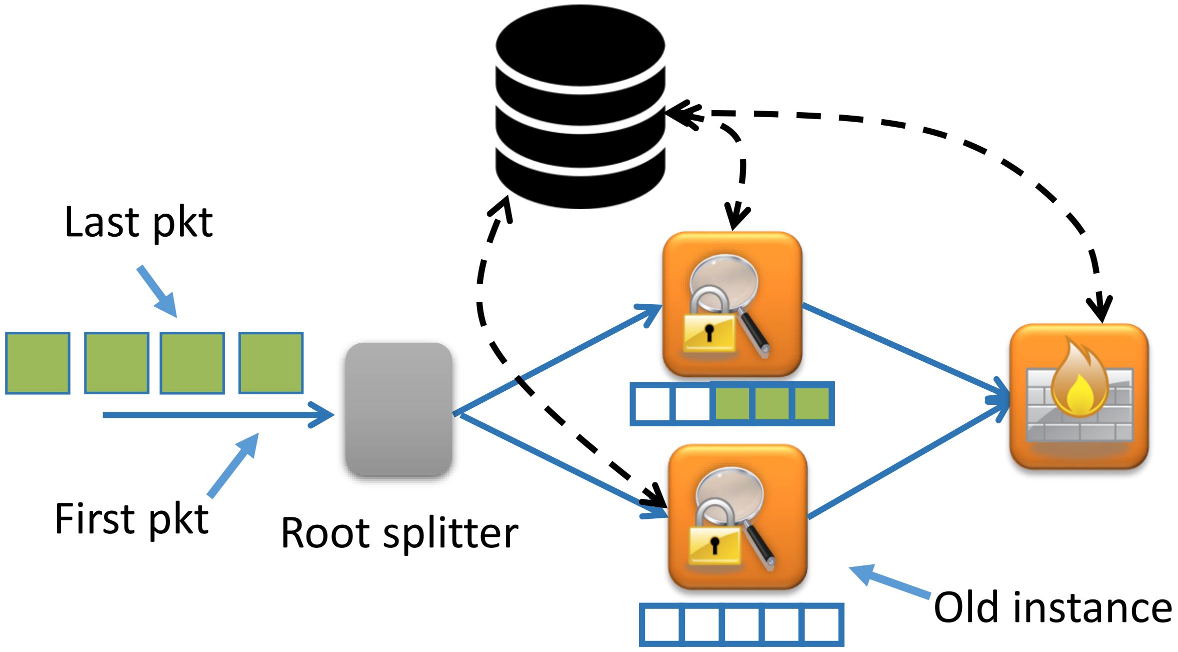
- CHC marks the last packet going to the old instance and first packet going to the new instance
- Ownership information encoded as metadata of state objects is used to ensure consistent handover of ***per-flow state***



# CHC – Elastic Scaling

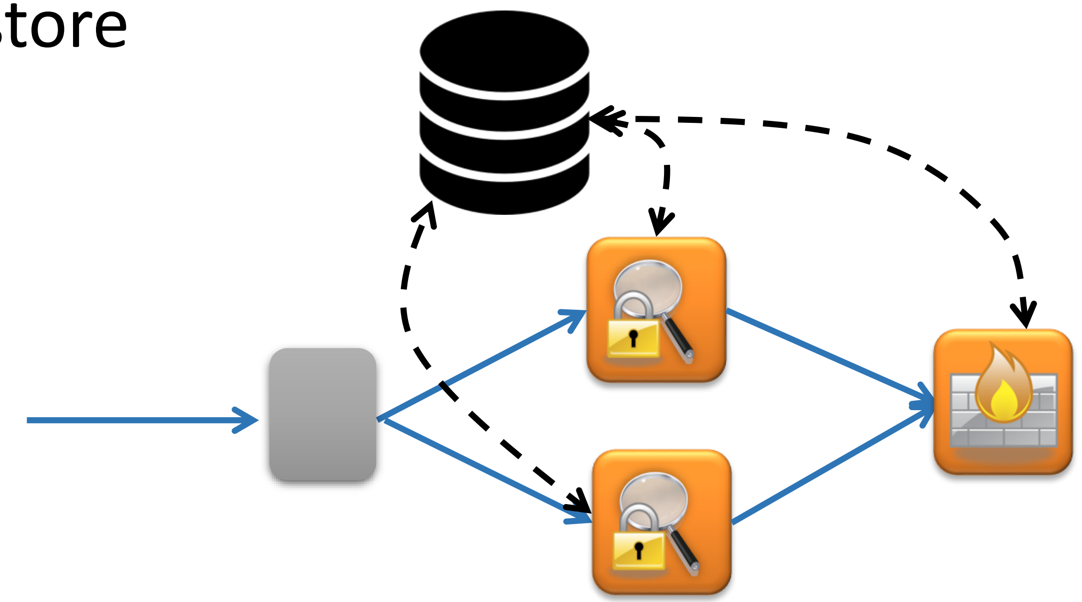
- CHC marks the last packet going to the old instance and first packet going to the new instance
- Ownership information encoded as metadata of state objects is used to ensure consistent handover of ***per-flow state***
- ***Cross-flow state*** does not require any special handling as operation offloading is used to update it



# CHC – Fault Tolerance

CHC provides fault tolerance for:

- NF instance
- Root splitter
- Datastore



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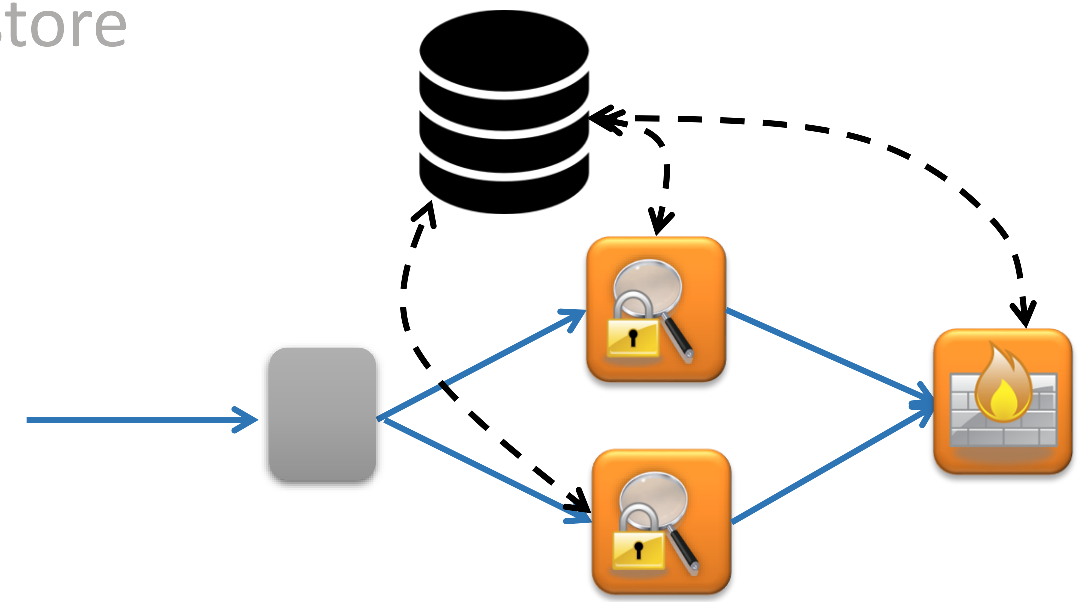
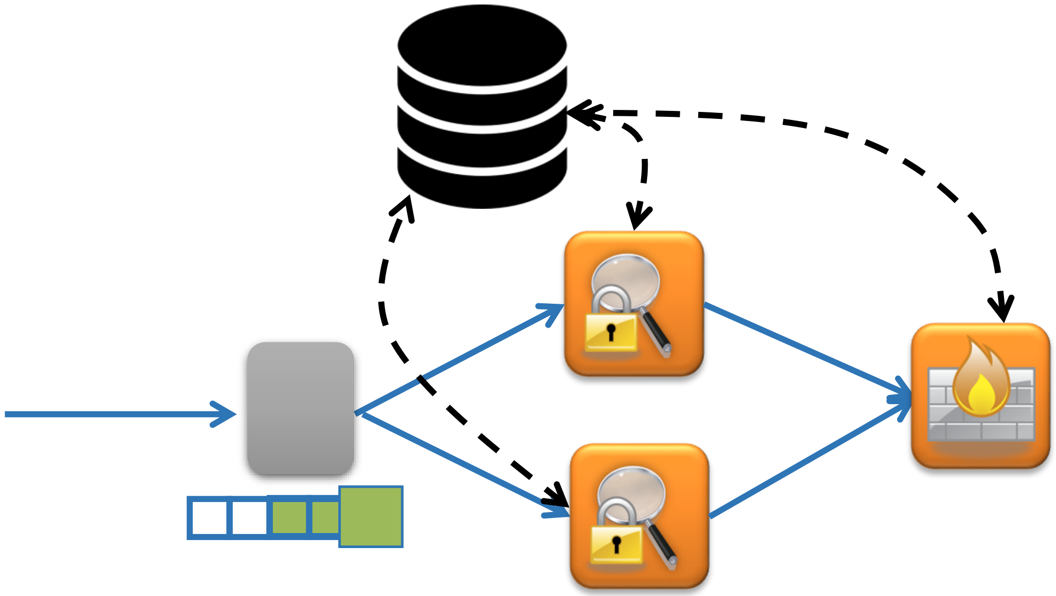


# CHC – Fault Tolerance

NF instance failure recovery:



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NF instance failure recovery:

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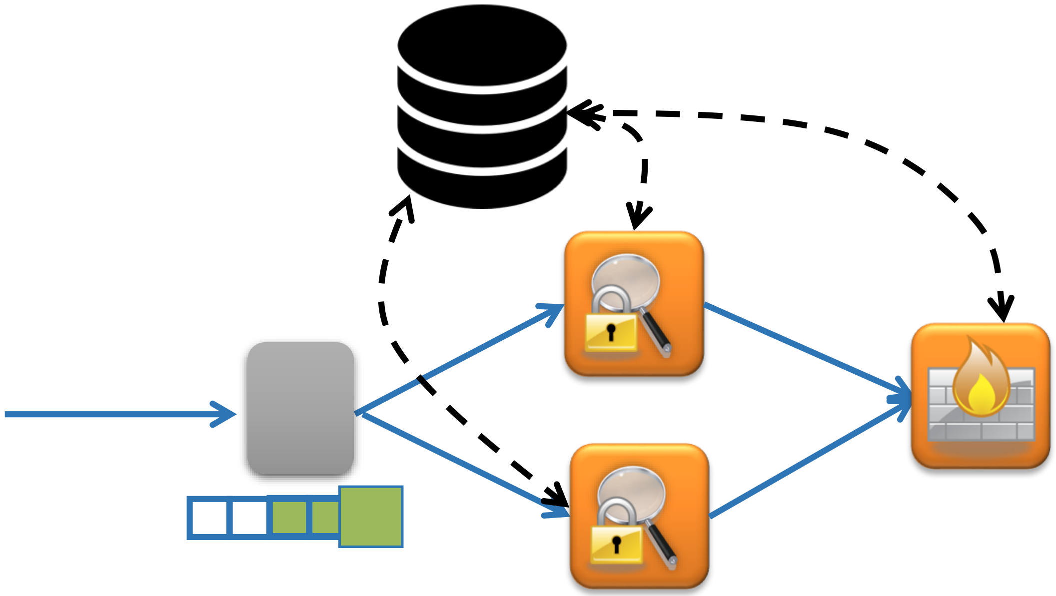

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NF instance failure recovery:

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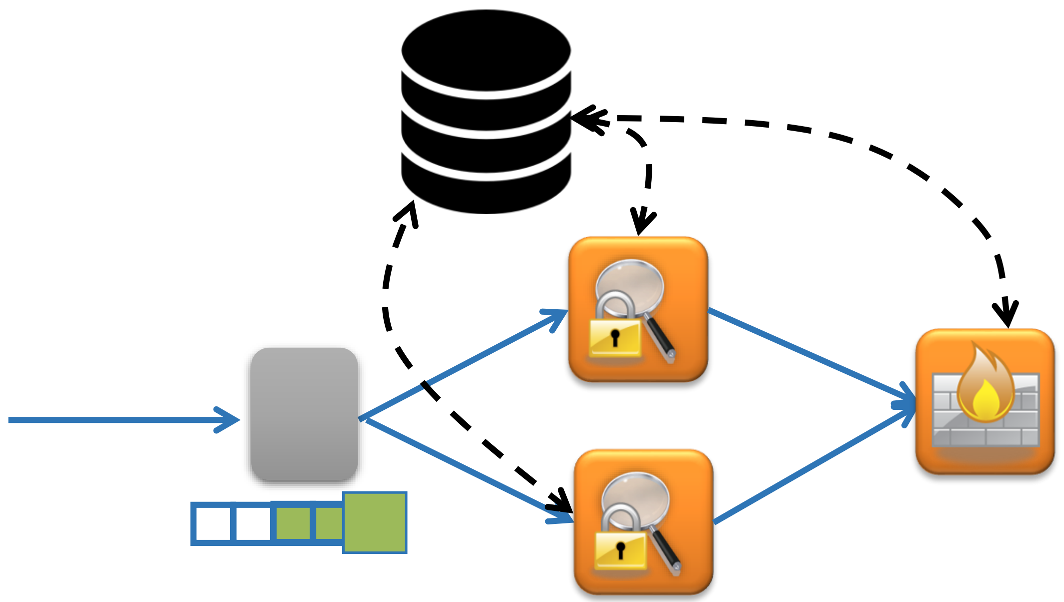

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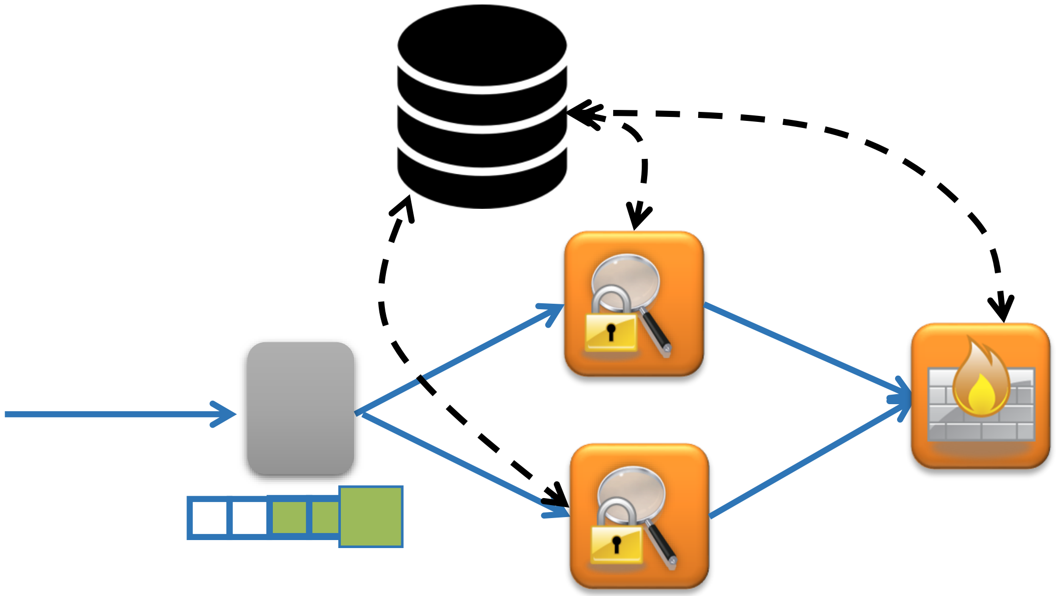

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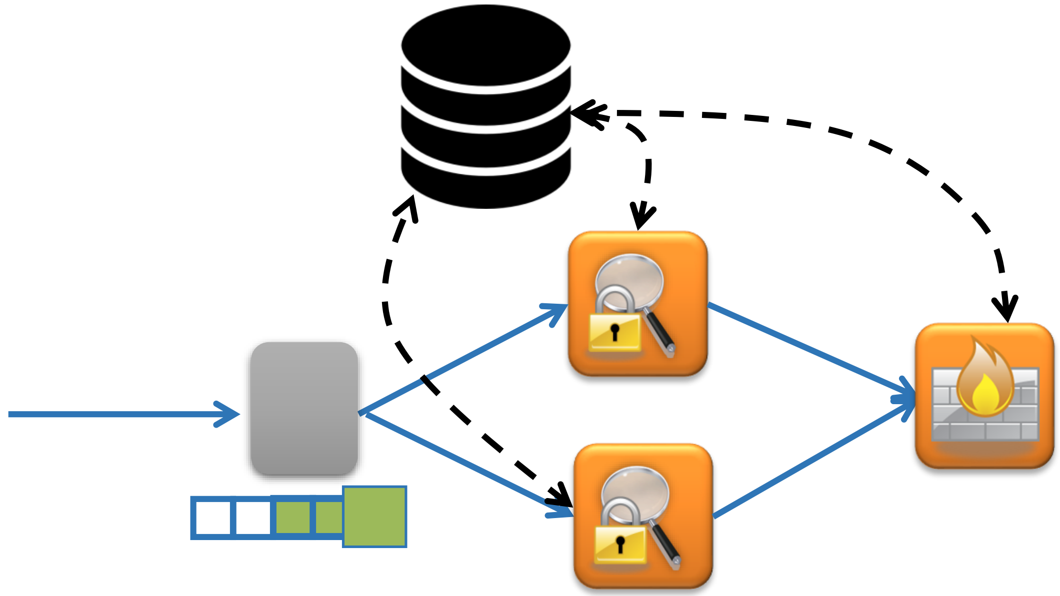
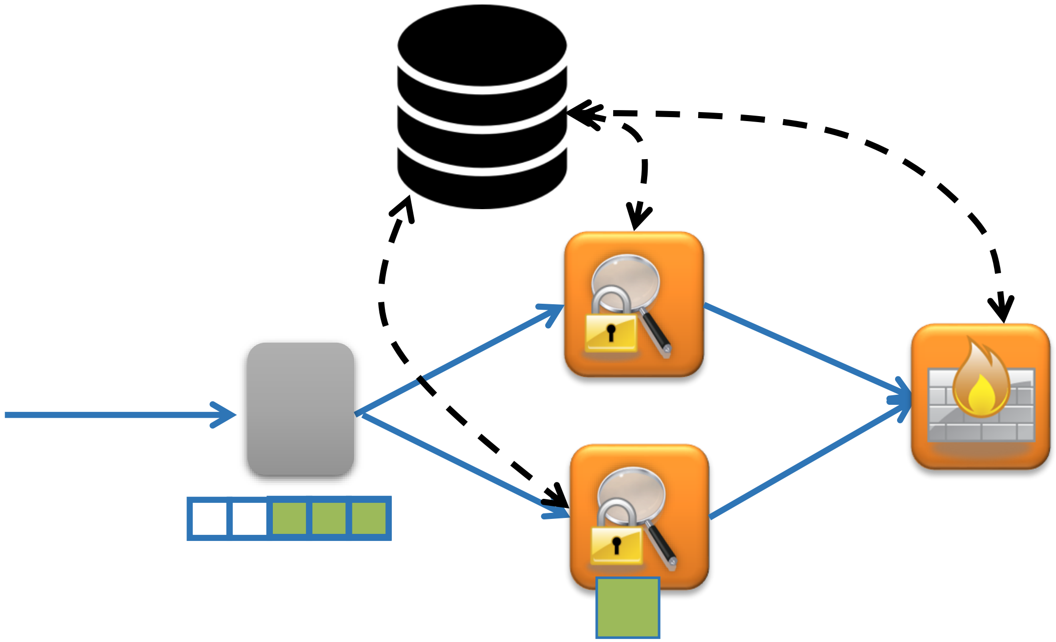


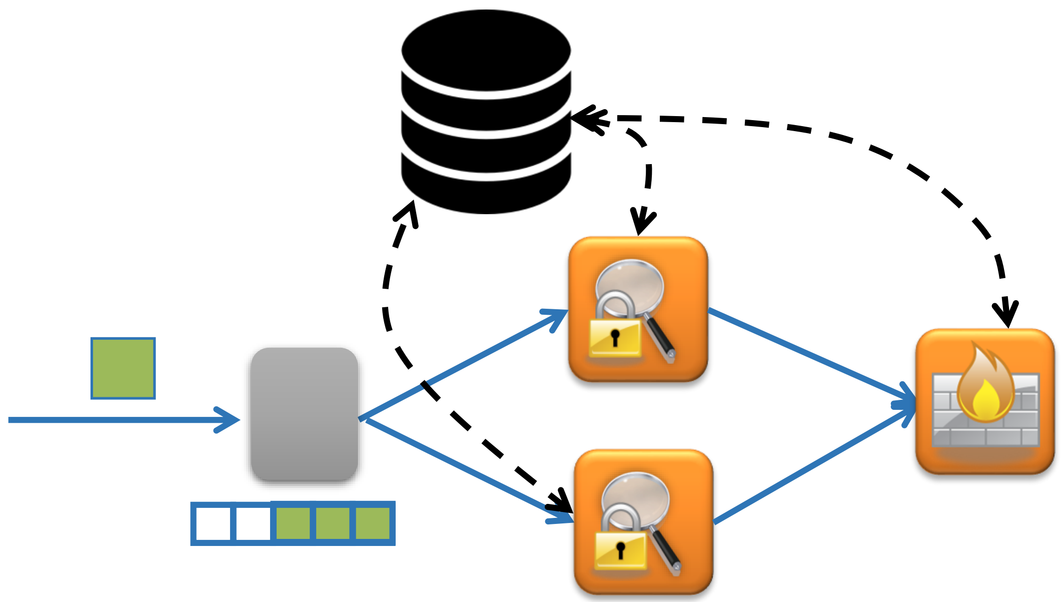
# CHC – Fault Tolerance

NF instance failure recovery:

- Failover instance takes over
- Datastore associates the ***failover instance ID*** with the relevant state
- Root ***replays*** the packet
- Metadata is used to ***suppress duplicate*** state-update and processing

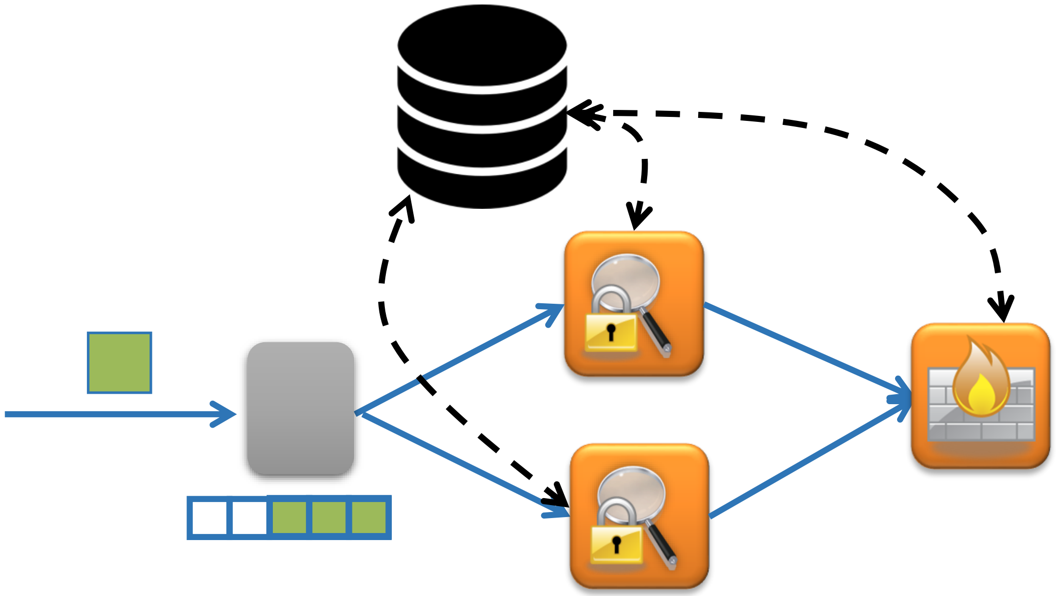


# CHC – Straggler Mitigation



# CHC – Straggler Mitigation

- Metadata (logical clocks) is used to suppress duplicate state updates at the datastore and duplicate packets at downstream NFs



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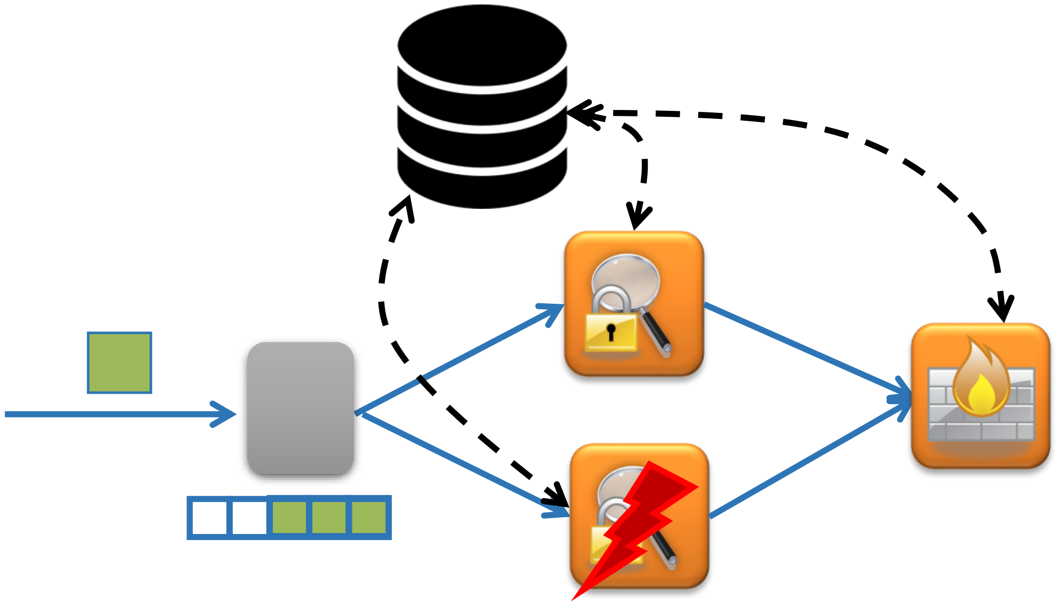

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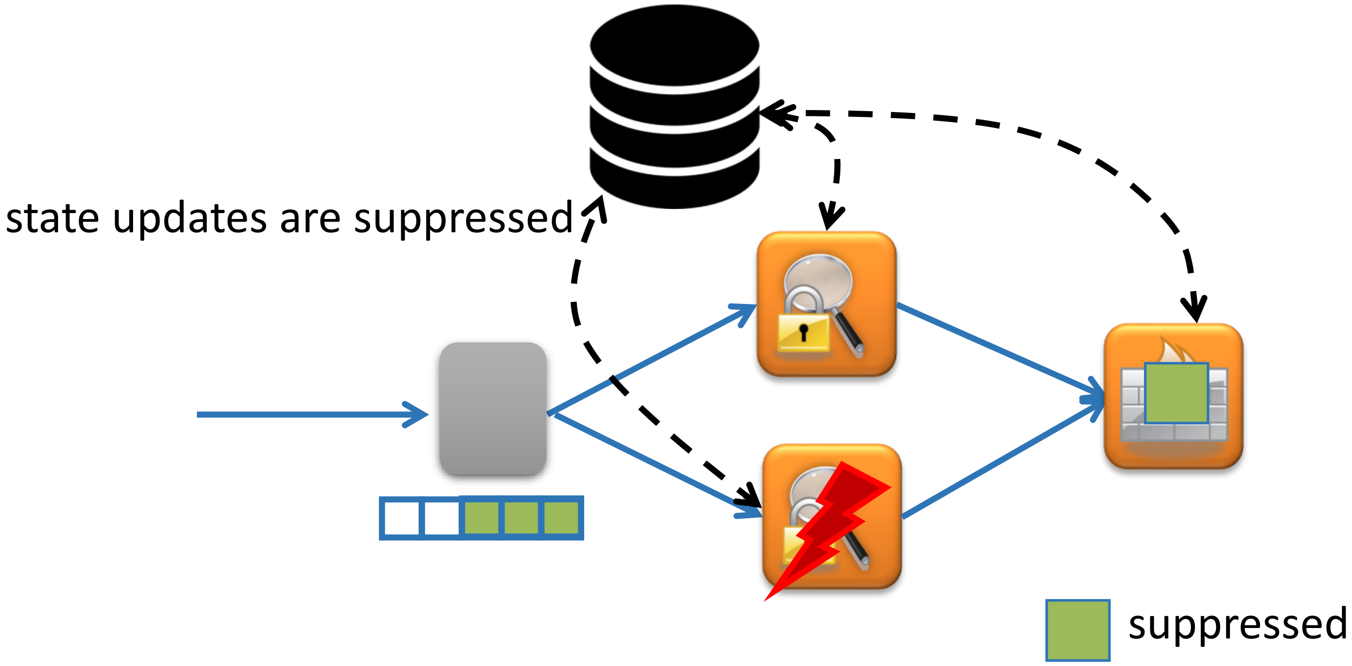

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- Prototype is implemented in C++
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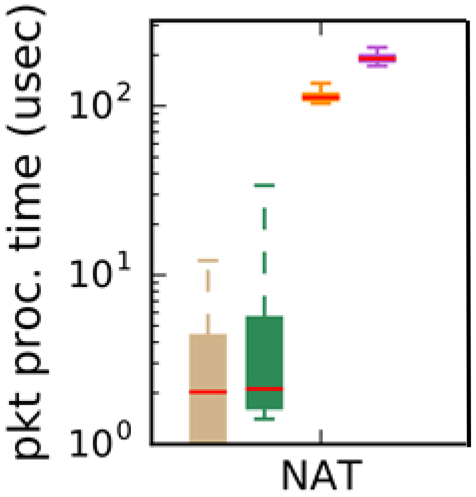
- We implemented four NFs on top of CHC
  - NAT
  - Trojan detector
  - Portscan detector
  - Load balancer

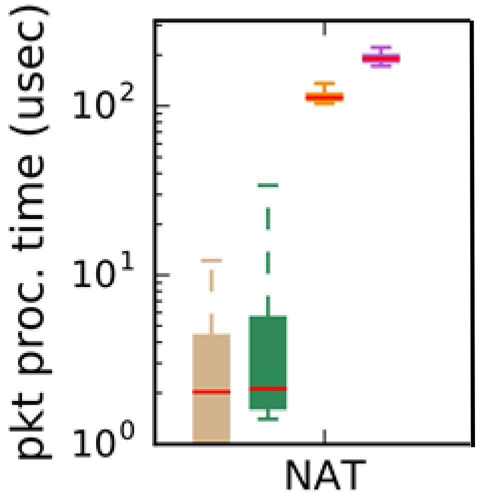
# Evaluation – Performance




| State variable | Scope |
|---|---|
| Port mapping | per-flow |
| Total TCP pkt count | cross flow |
| Total IP pkt count | cross low |

Traditional NF with infinite capacity

# Evaluation – Performance

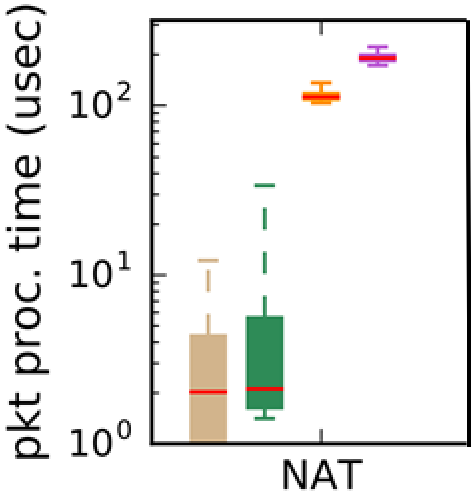



| State variable | Scope | State Externalization |
|---|---|---|
| Port mapping | per-flow | ✔ |
| Total TCP pkt count | cross flow | ✔ |
| Total IP pkt count | cross low | ✔ |

Traditional NF with infinite capacity

Externalized state operations

# Evaluation – Performance



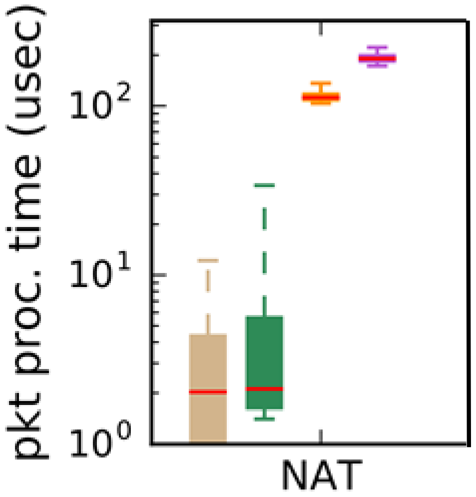

| State variable | Scope | State Externalization | Caching |
|---|---|---|---|
| Port mapping | per-flow | ✓ | ✓ |
| Total TCP pkt count | cross flow | ✓ | |
| Total IP pkt count | cross low | ✓ | |

Traditional NF with infinite capacity

Externalized state operations

State externalization with caching

# Evaluation – Performance




| State variable | Scope | State Externalization | Caching | Asynch. + op offload |
|---|---|---|---|---|
| Port mapping | per-flow | ✔ | ✔ | |
| Total TCP pkt count | cross flow | ✔ | | ✔ |
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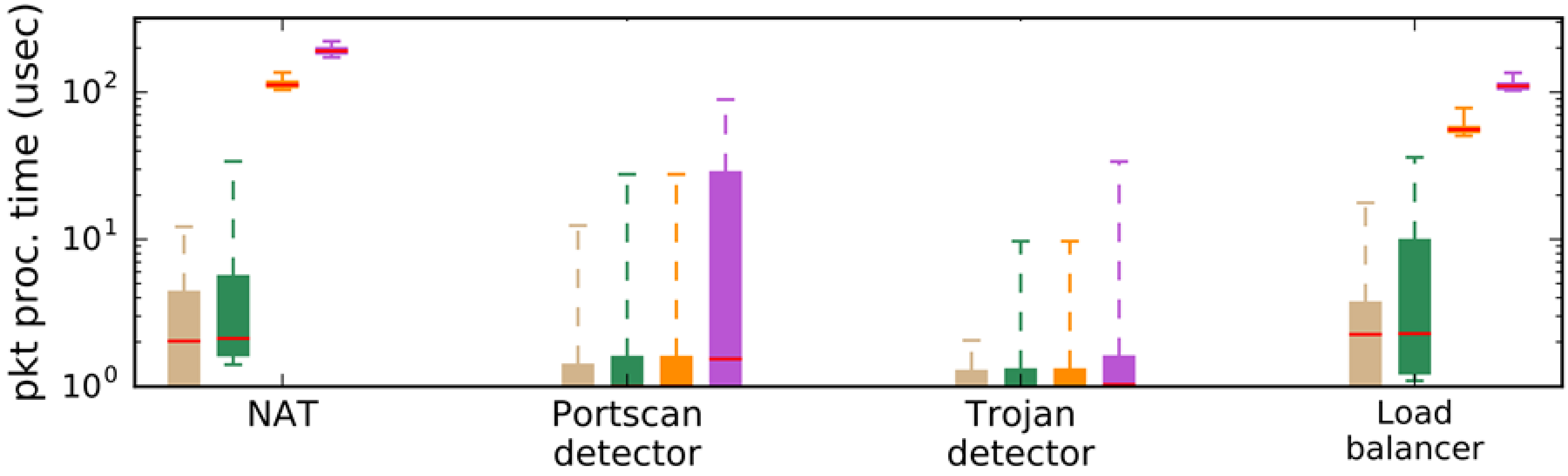
- Traditional NF with infinite capacity
- Externalized state operations
- State externalization with caching
- State externalization with caching and asynchronous + offloaded updates

# Evaluation – Performance




Traditional NF with infinite capacity

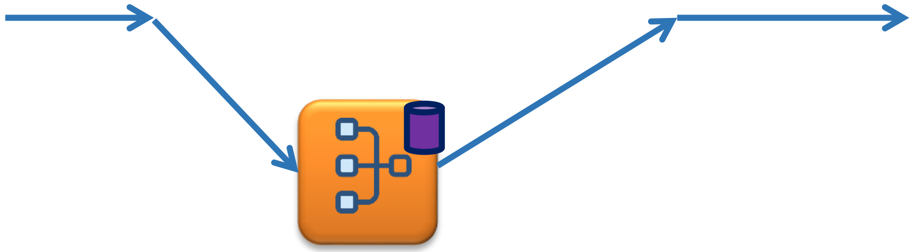
Externalized state operations

State externalization with caching

State externalization with caching and asynchronous + offloaded updates

Less than ***0.6μs*** increase in the median per-NF packet processing latency

# Evaluation – Dynamic Actions



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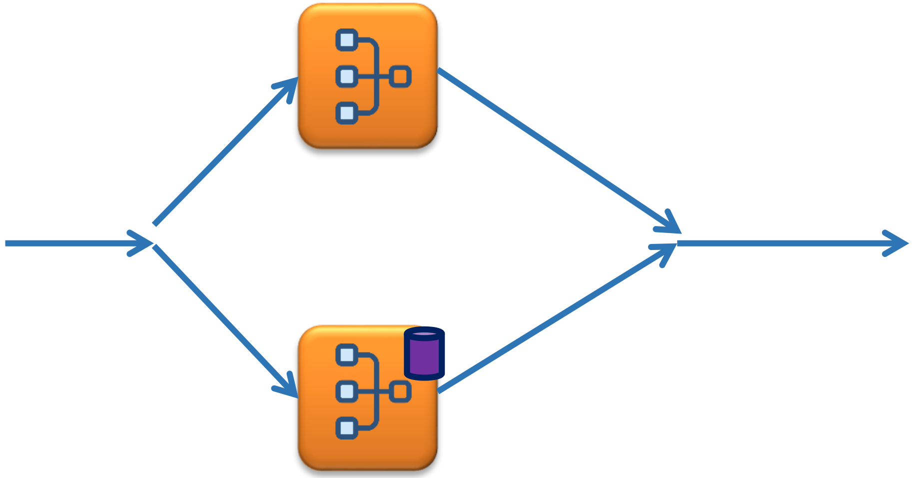

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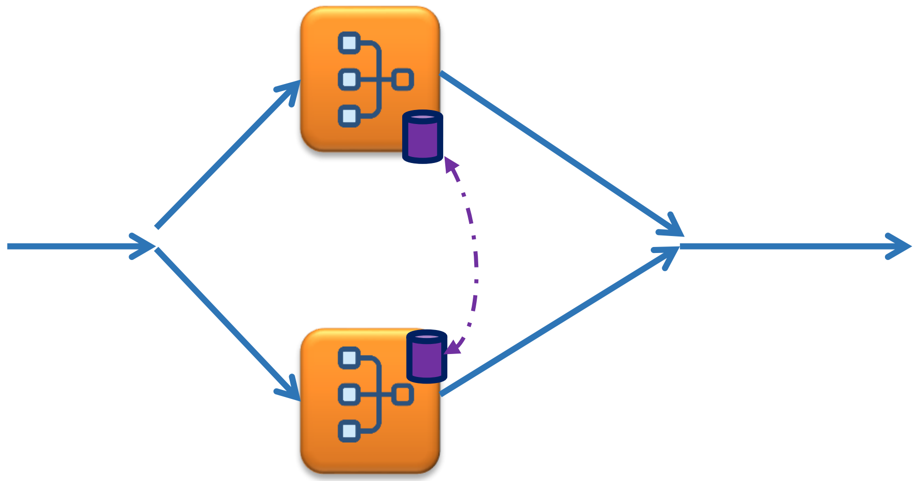

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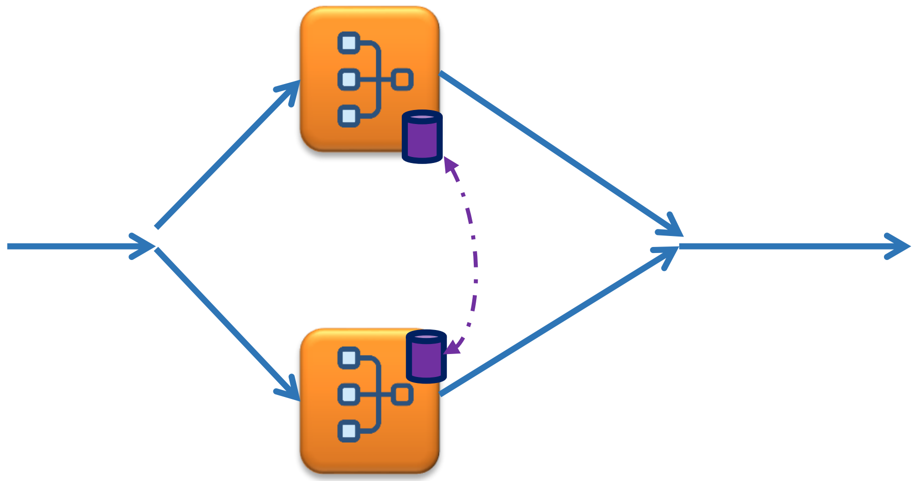
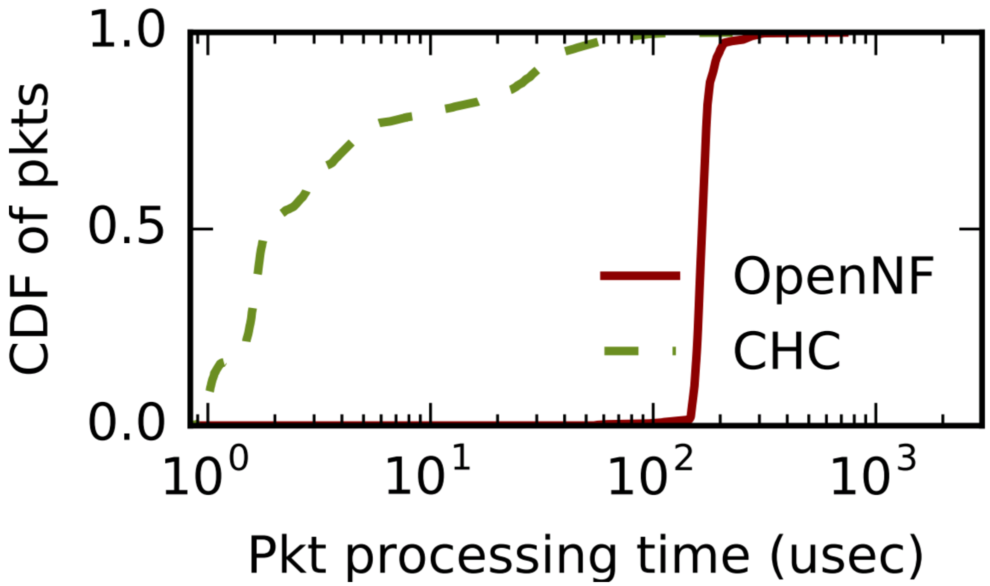


During cross instance state sharing



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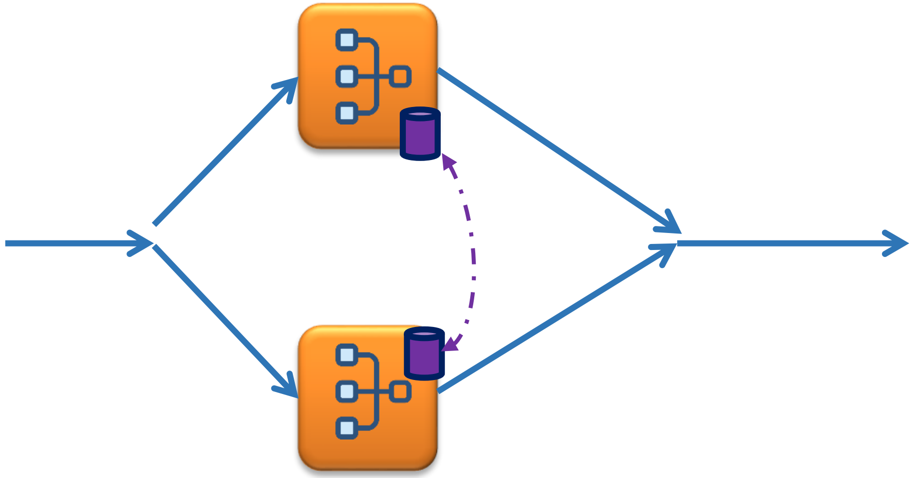

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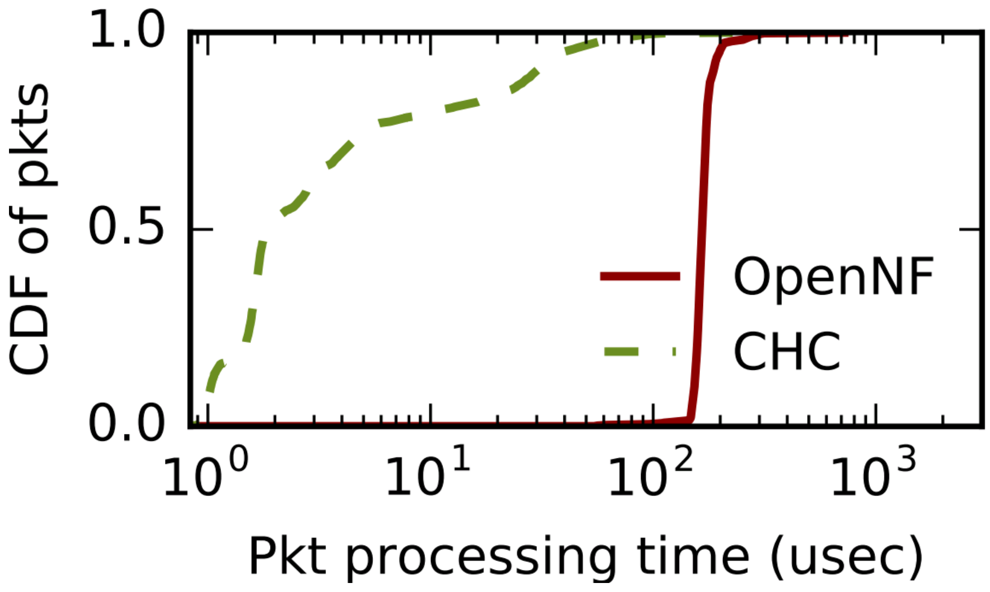
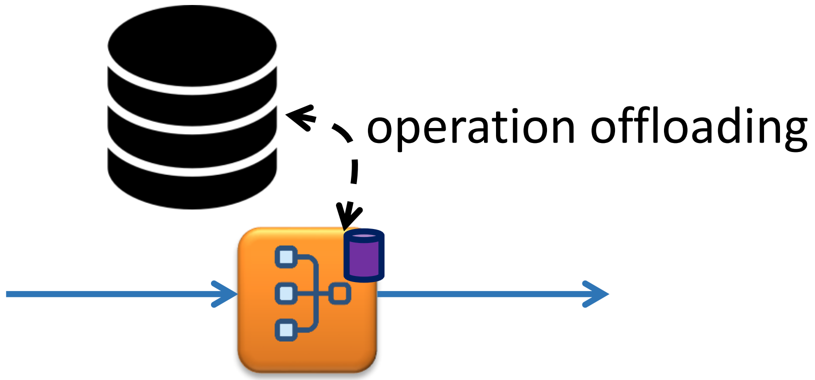



75th%-ile latency of CHC is ***20 times* lower than** OpenNF

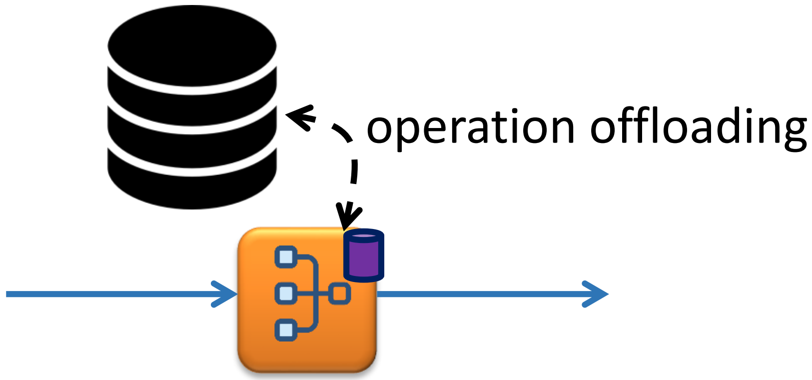
# Evaluation – Dynamic Actions

CHC

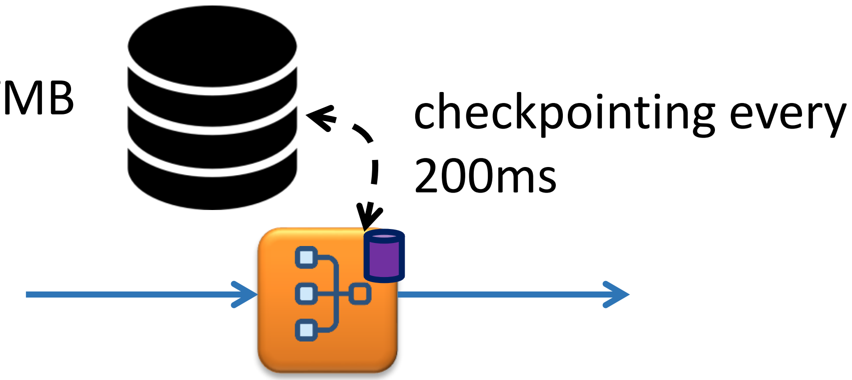


# Evaluation – Dynamic Actions

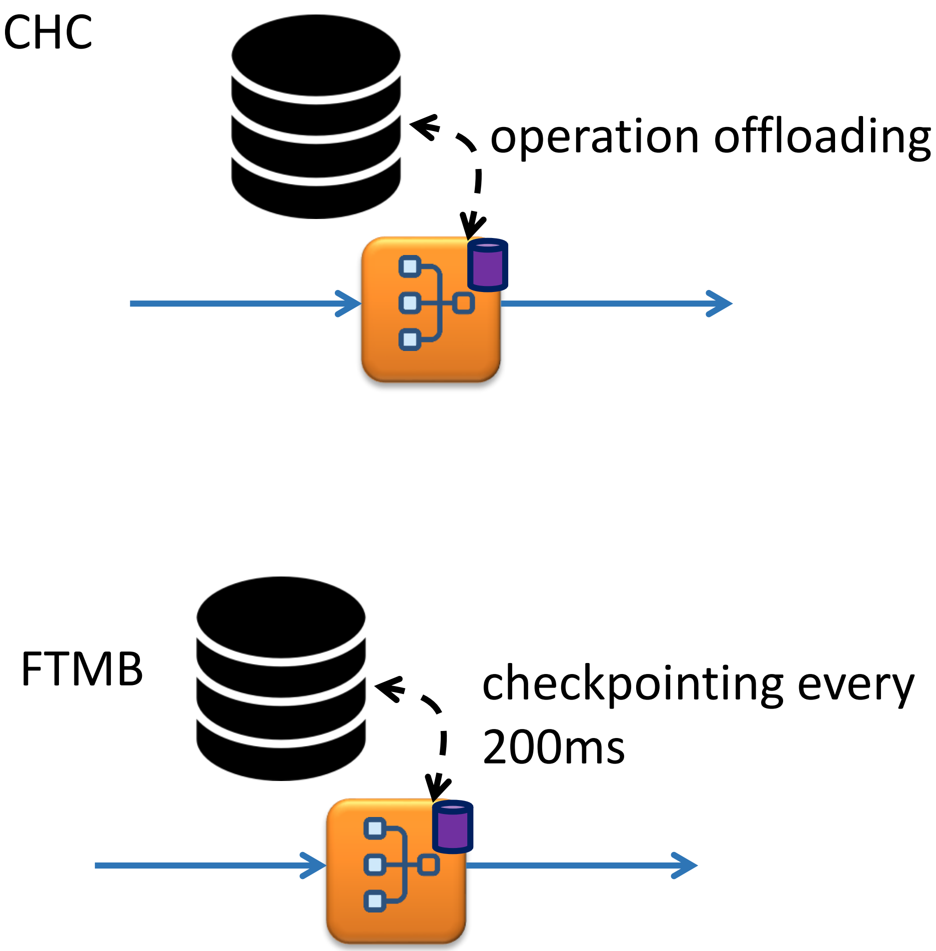
CHC



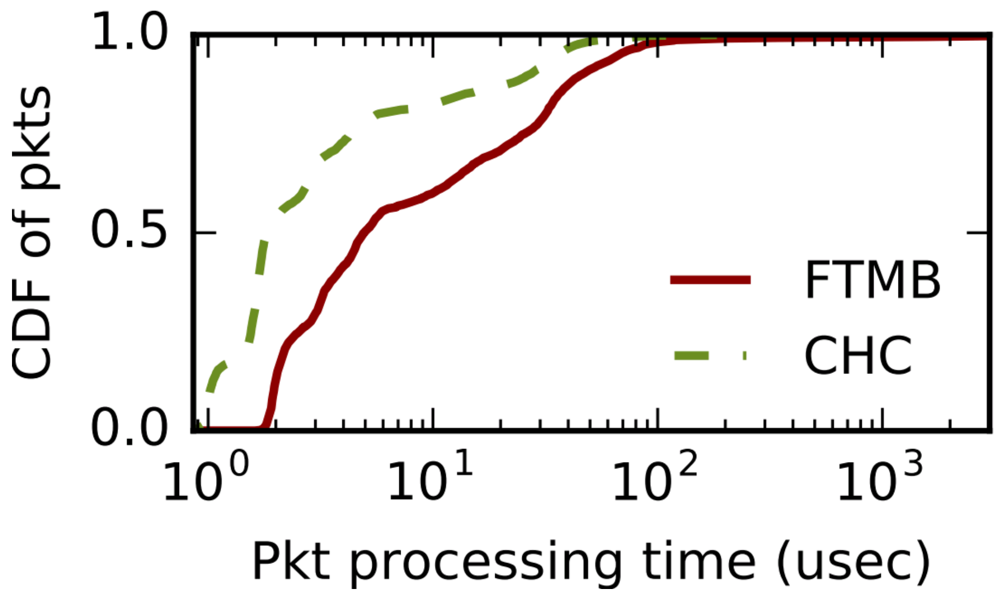

FTMB



# Evaluation – Dynamic Actions




Ensuing Fault tolerance



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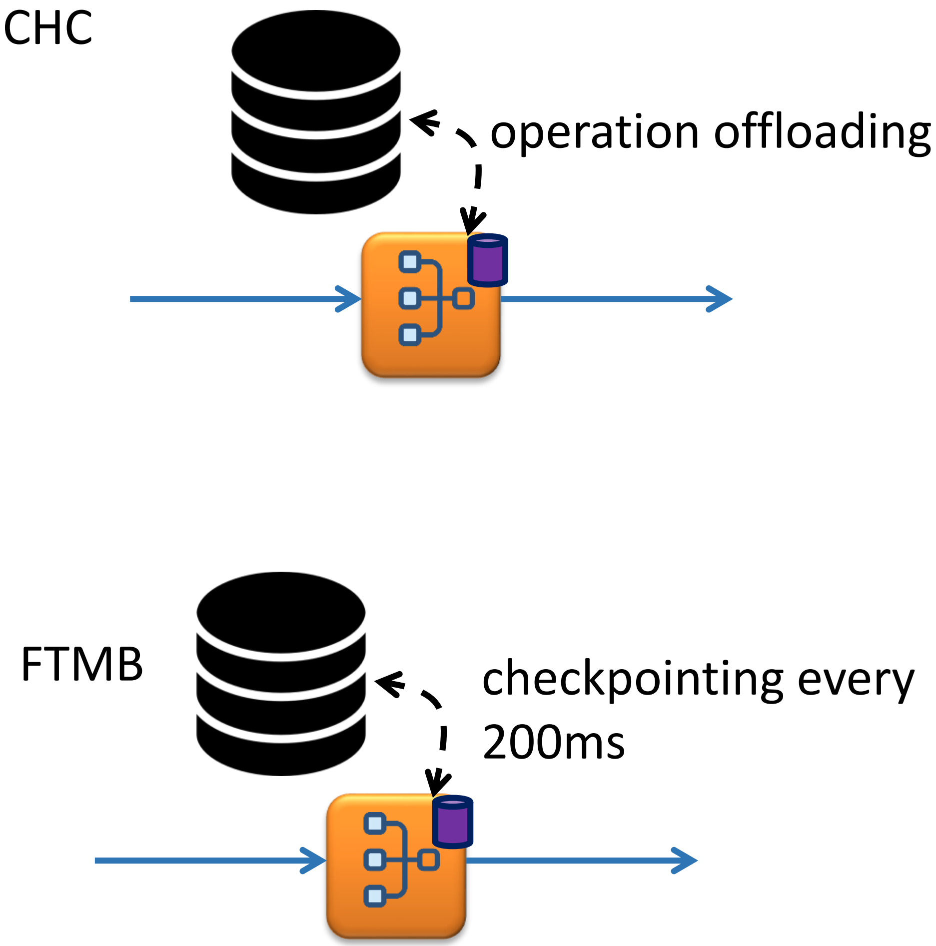
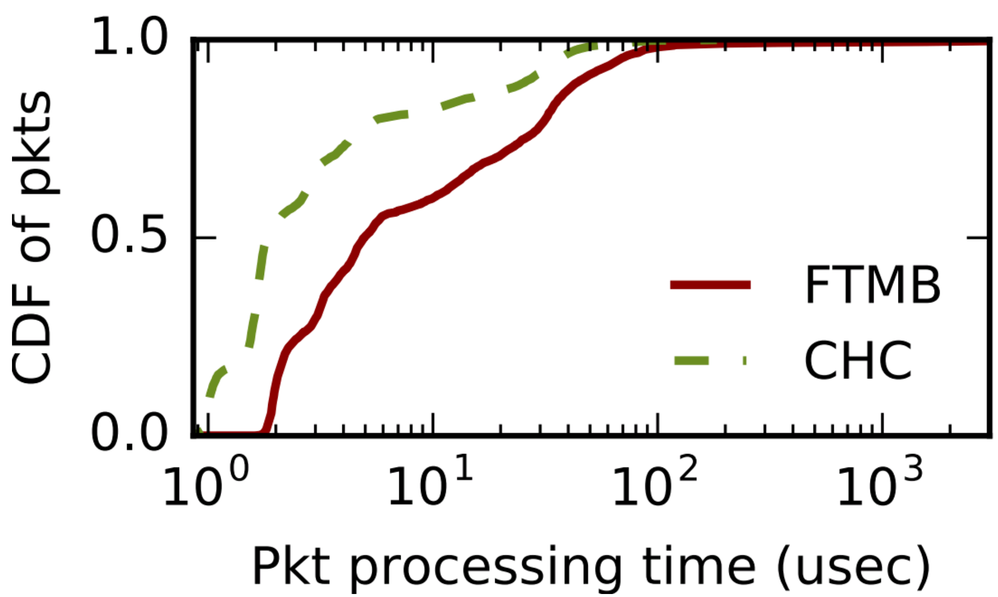
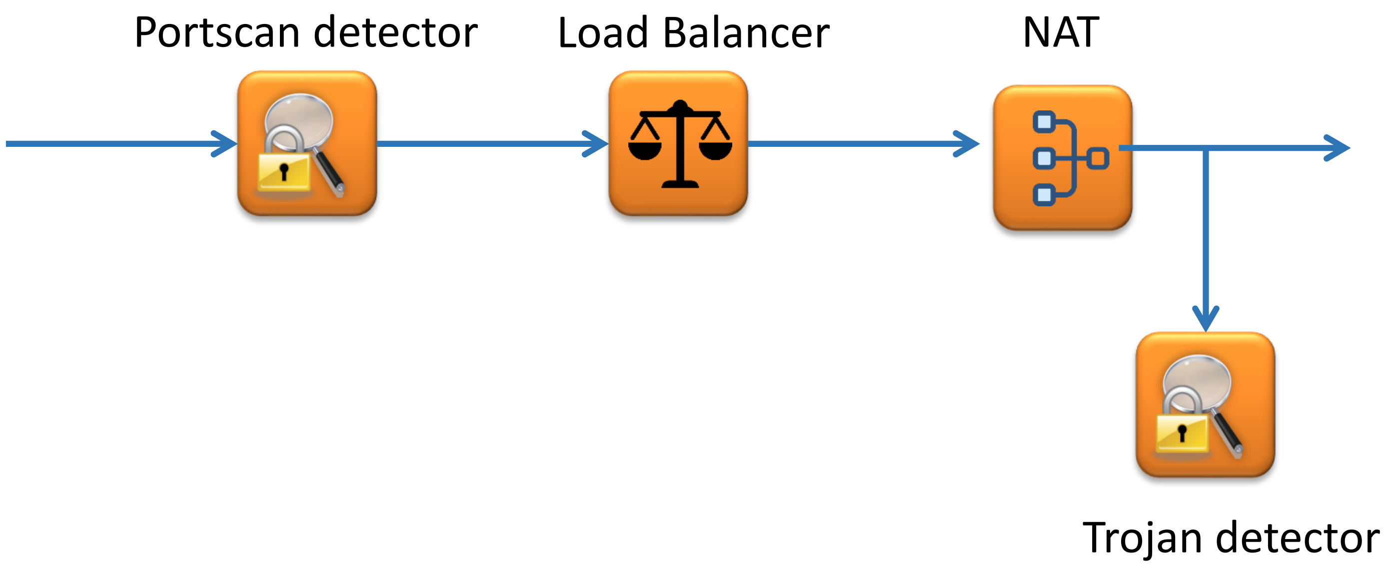



Ensuing Fault tolerance




75th%-ile latency of CHC is ***6 times* lower than** FTMB

# Evaluation




CHC operates at line rate with an end-to-end median per packet processing overhead of ***11.3us***

# Evaluation

- State management performance
- Metadata overhead
- Correctness requirements:
  - State availability
  - Cross instance state transfer
  - Cross instance state sharing
  - Chain wide ordering
  - Duplication suppression
  - Fault tolerance

# Summary

- CHC supports output equivalence and high performance state management for NFV chains
- It hides the complexity of handling states during dynamic actions (elastic scaling and failure recovery)
- It relies on managing state external to NFs, but couples it with several caching and state update algorithms to ensure low latency