Breaking Service Function Chains with *Khaleesi*

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Service Function Chaining (SFC)

Network policies often require packets to traverse an ordered set of Network Functions

Service chain for a Web Service

Service chain in enterprise Data Center Networks

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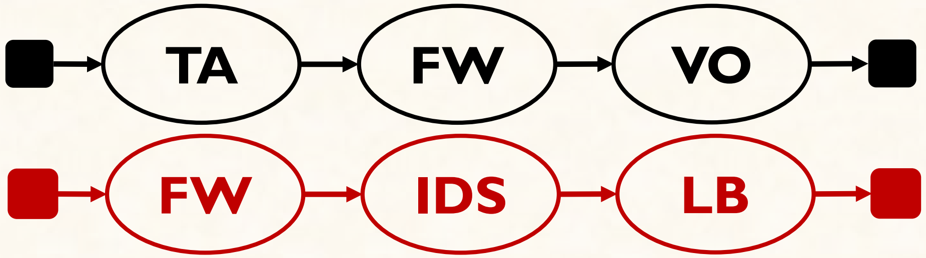
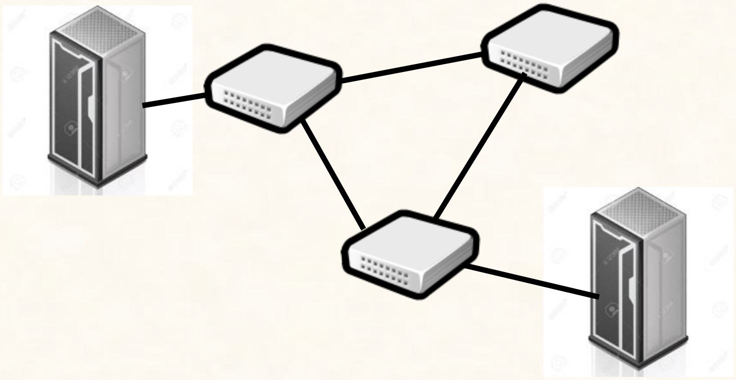
Traditionally, network functions have been realized by hardware middleboxes

SFC Orchestration in NFV

Given



A set of SFC requests



A set of Physical Resources
(Servers, Switches, Links)

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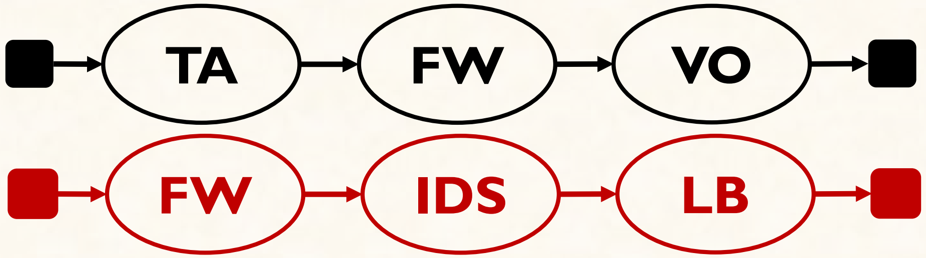

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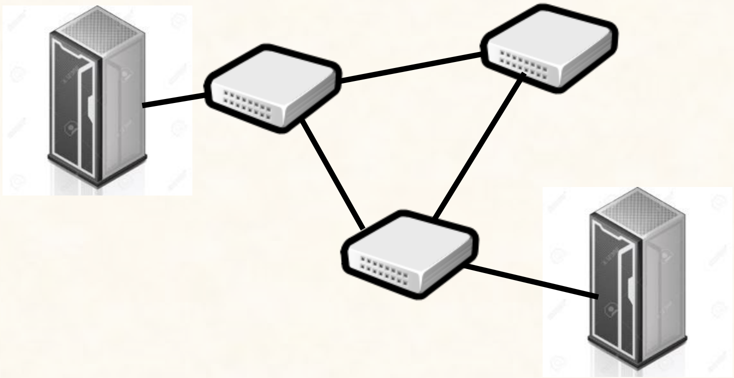

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Determine

Placement of NFs on Servers

Traffic Routing between VNFs

Objective: Minimize OPEX/ Energy Cost/Network B.W, or Maximize Acceptance Ratio *etc.*

SFC Orchestration: State-of-the-art

O(100) research papers on the topic

Different aspects have been considered

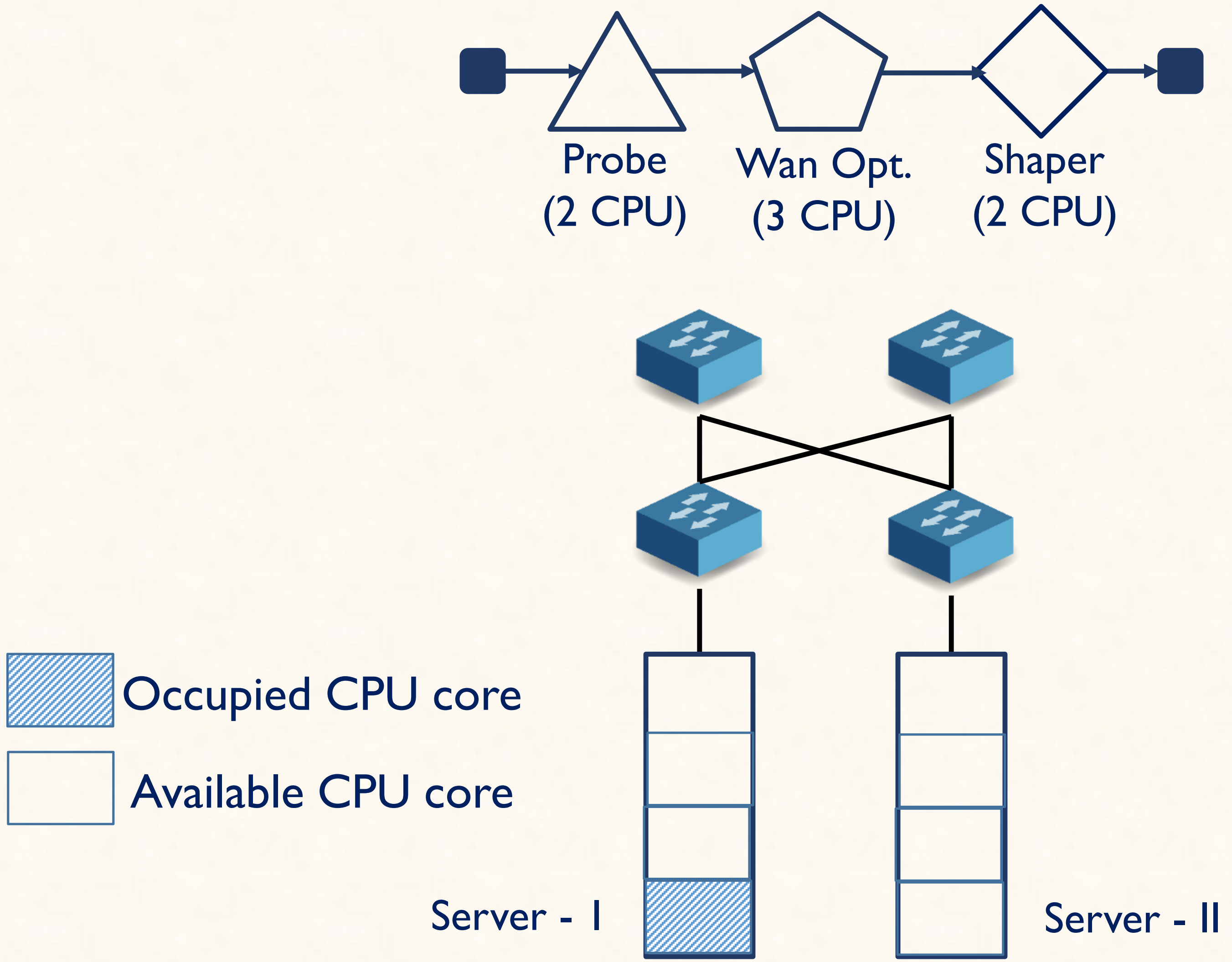
Minimization of energy, network bandwidth, SLO violation, *etc.*
Maximization of availability, acceptance ratio, *etc.*

In most cases, the SFC is considered *rigid*, *i.e.*, *traversal order of the NFs cannot be modified at all*

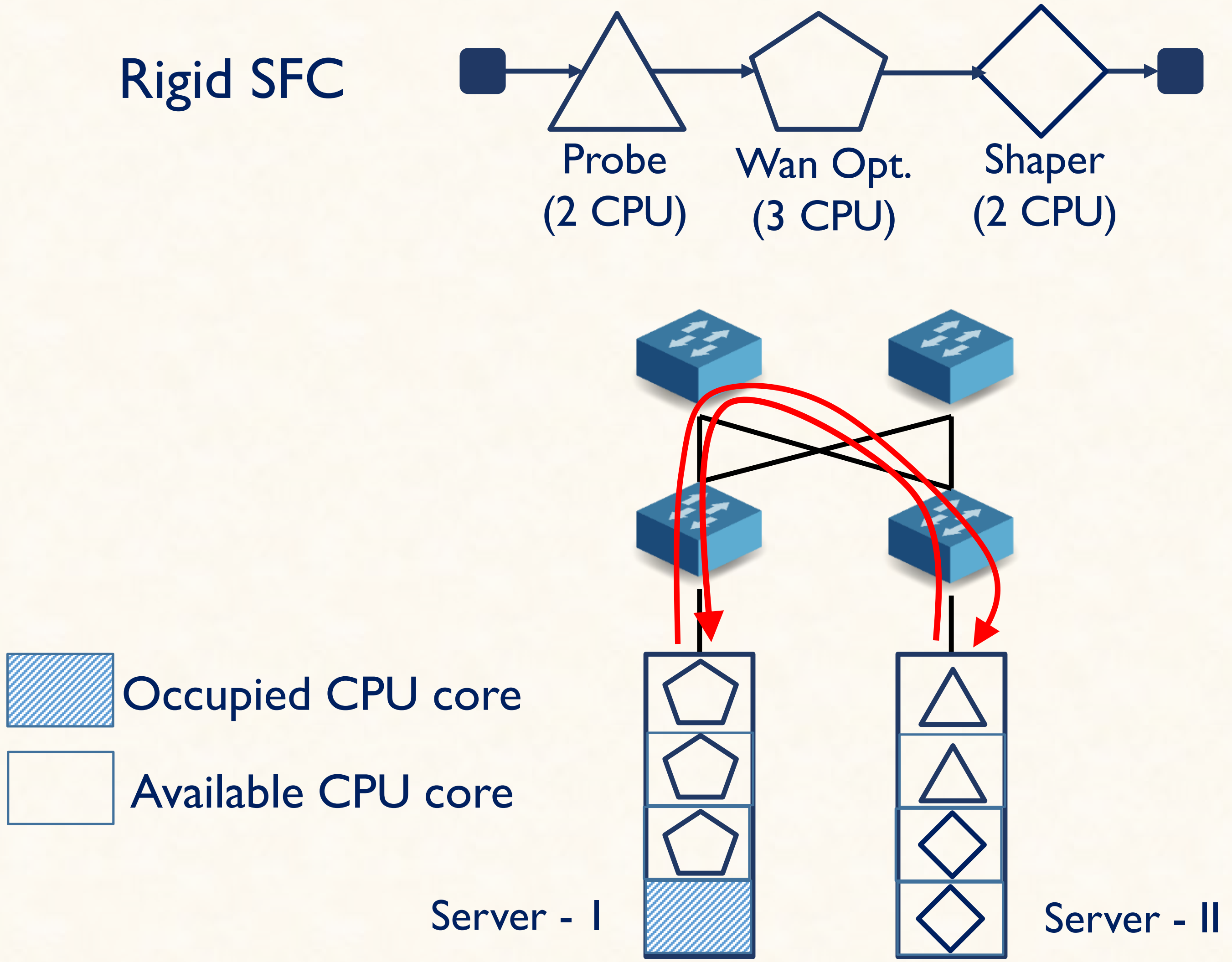
Question:

Can we perform better resource allocation *if we break the traversal order* in an SFC?

Illustrative Example



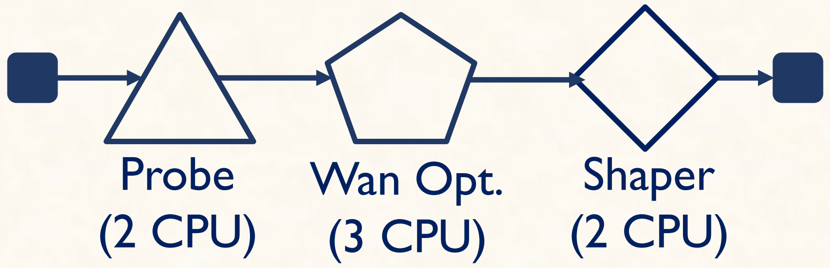
Resource Allocation for Rigid SFC

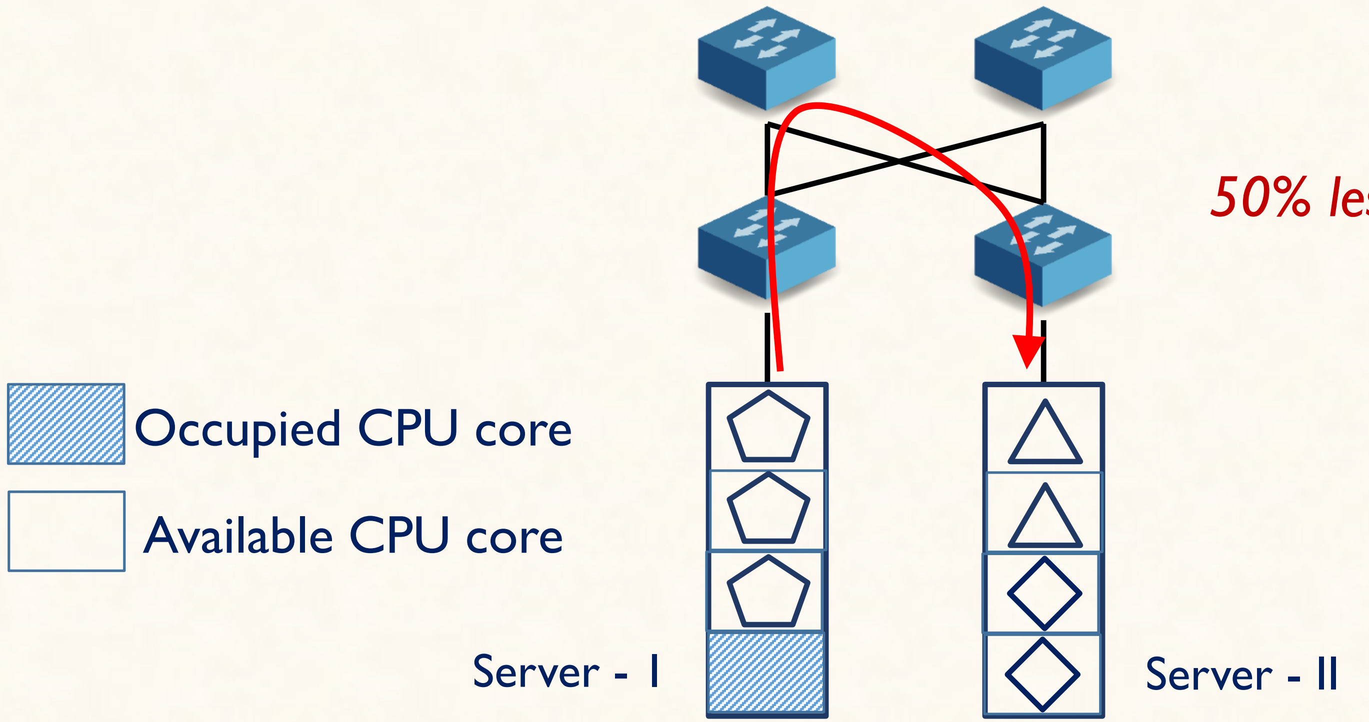


Resource Allocation for Flexible SFC

Flexible SFC

(Probe and Wan Opt. can be swapped)





50% less network hops

More Questions

How can we tell if NF traversal order can be *broken*?

How to *exploit* flexible SFCs in resource allocation?

How much *benefit* can we get from flexible SFCs?

Our Contributions

Question	Contribution
How can we tell if NF traversal order can be *broken*?	Theoretical analysis for detecting *re-order compatible* NFs
How to *exploit* flexible SFCs in resource allocation?	*Khaleesi**: Suit of solutions for SFC Orchestration, *while breaking NF traversal order*
How much *benefit* can we get from flexible SFCs?	Empirical evaluation of *benefits*

*Character from the popular fantasy novel *A Song of Ice and Fire* (adapted as TV series *Game of Thrones*), who is also known as *the breaker-of-chains*

Flexible SFC: State-of-the-art

Language and Data Model[1,2]

Flexibility is part of input; does not demonstrate any quantifiable benefit.

NF Execution Parallelization[3,4]

Requires additional specialized components

Flexibility is determined from NF properties for finding Optimal Solution; empirically evaluated quantifiable benefits demonstrated

1. S. Mehraghdam *et al.*, "Placement of services with flexible structures specified by a yang data model," IEEE NetSoft, 2016
2. S. Mehraghdam *et al.*, "Specifying and placing chains of virtual network functions," IEEE CloudNet, 2014
3. Y. Zhang *et al.*, "Parabox: Exploiting parallelism for virtual network functions in service chaining," ACM SOSR, 2017
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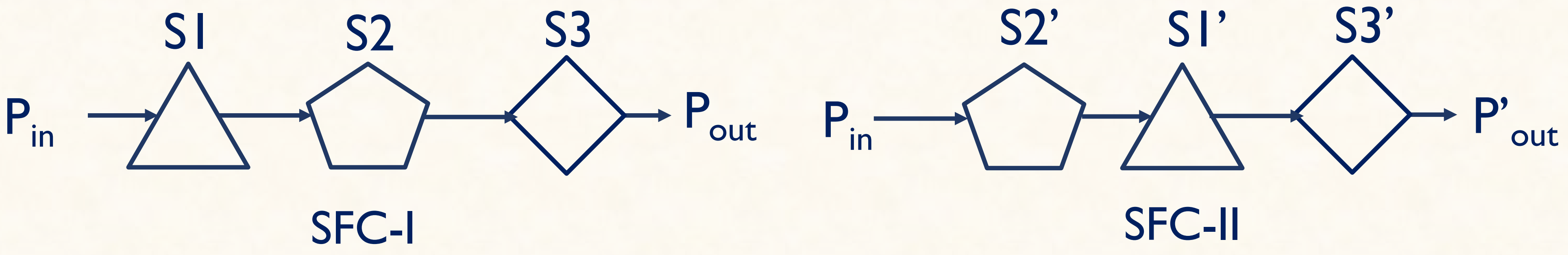
How to determine *re-order compatibility*?

When is a pair of NFs re-order compatible?

When swapping their order in an SFC results in *semantically equivalent* SFCs

What is *semantic equivalence*?



SFC-I & SFC-II are *semantically equivalent iff*
$P'_{out} = P_{out}$ and (S1,S2,S3) =(S1',S2',S3')

Conditions for Re-order Compatibility

NF Operation involves:	Reads/Write *Packet Headers* → *Interest fields*
	Update internal state based on *packet header* → *State fields*

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	Firewall	Proxy	IPS	Shaper	NAT	DPI	WANX	Probe
Firewall			✓	✓		✓	✓	
Proxy			✓	✓		✓		
IPS	✓	✓		✓				✓
Shaper	✓	✓	✓			✓	✓	
NAT							✓	
DPI	✓	✓		✓				✓
WANX	✓			✓	✓			✓
Probe			✓			✓	✓	

Re-order compatibility matrix of commonly used enterprise NFs

Reorder Compatibility + SFC Orchestration

Re-order Compatibility + SFC Orchestration
= *Flexible SFC Orchestration*

Khaleesi: A suit of solutions to Flexible SFC Orchestration

OPT-Khaleesi

ILP-based Optimal Solution
(NP-hard)

FAST-Khaleesi

Greedy Heuristic

Assumptions

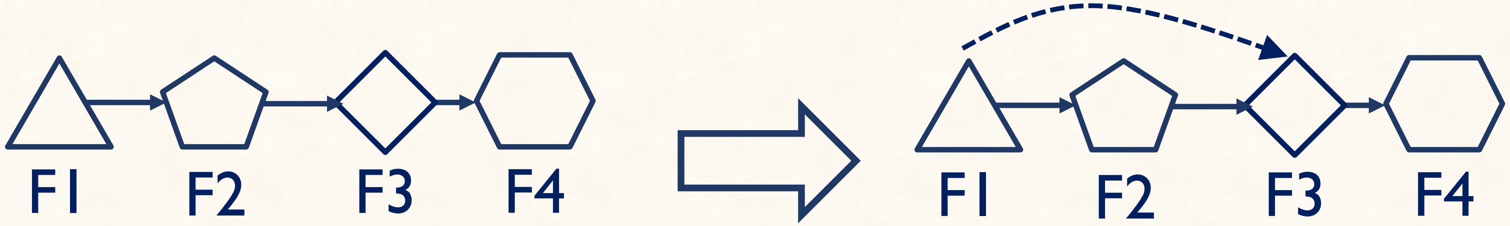
Linear Chain of NFs (no branches)

No change of data rate after swapping

Heterogeneous servers

OPT-Khaleesi*

Augment the SFC with additional links according to re-order compatibility matrix such that all valid chains can be traced



Reorder(F1,F2) = true

If F2 is swapped with F1 then there can be a link from F1 to F3

ILP *selects the optimal set of virtual links* to form a valid SFC and performs joint NF placement and virtual link routing while minimizing network bandwidth usage

* Details are in the paper

OPT-Khaleesi*

Decision Variables

VNF Placement on Servers, Virtual Link Selection, Virtual Link Routing

Constraints

- Select exactly F - 1 virtual links (F = number of NFs)
- Selected virtual links should form a chain semantically equivalent to the input

* Details are in the paper

FAST-Khaleesi: 4-Step Algorithm

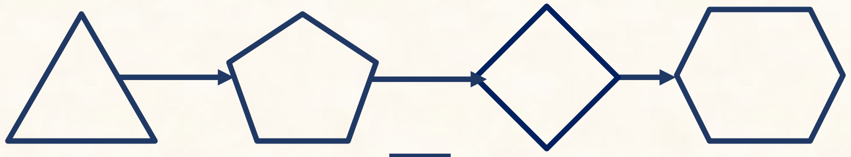
Step-I: Generate all possible SFCs

Step-II: Find Candidate Servers

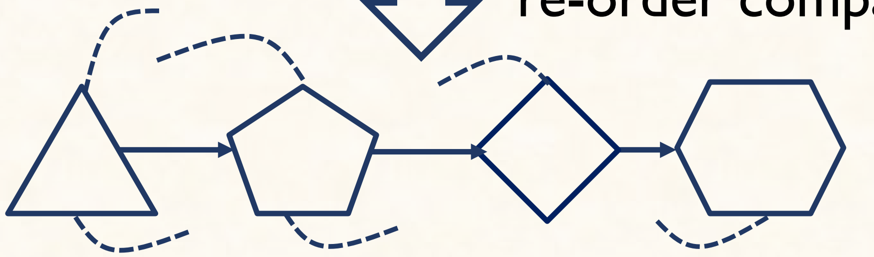
Step-III: Place VNFs on servers to minimize cross-server traffic

Step-IV: Inter-server Routing

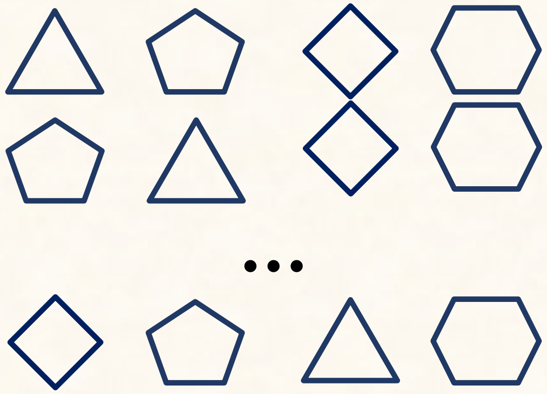
Step – I: SFC Generation



Augment edges according to re-order compatibility matrix



DFS Traversal to generate all chains



Step – II: Determine Candidate Servers

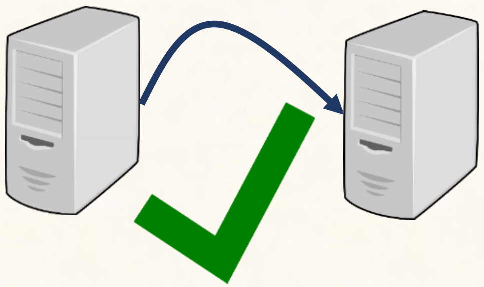
II.1 Filter servers based on NF's CPU requirement

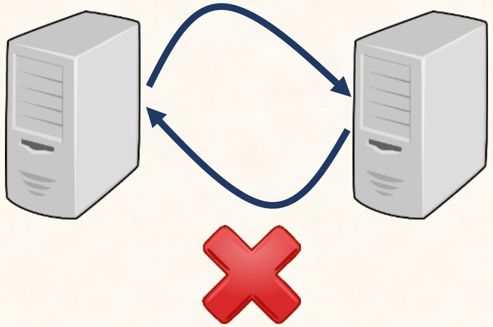
II.2 Sort servers in decreasing order of *R*

$$R = \frac{\text{Residual number of cores}}{\text{Distance from ingress sw + Distance from egress sw}}$$

Prioritize servers with higher capacity and proximity to the SFC's ingress and egress nodes

Step – III, IV: VNF Placement & Routing





III.1 Traverse servers in decreasing order of R

III.2 Keep placing VNFs from the beginning of a chain using first fit algorithm

III.3 Determine the number of cross server virtual links

III.4 Pick placement with minimum number of cross-server link

IV. Route virtual links between servers using Dijkstra's algorithm

Evaluation: Setup

- Comparison scenarios
  - OPT-Khaleesi compared with *optimal rigid SFC orchestration**
  - *An existing heuristic** for rigid SFC orchestration fed with all possible chains
  - FAST-Khaleesi compared with OPT-Khaleesi
- Substrate network
  - Small size campus data center (23 nodes, 42 links)
  - Moderate size ISP network from RocketFuel (79 nodes, 147 links)
- SFC request
  - 3 – 6 NFs/request
  - Poisson process (4 – 10 SFC/100 time unit avg., 1000 unit avg. lifetime)
  - Both real and synthetic traffic matrix

* Bari, *et al.* "Orchestrating Virtualized Network Functions ", IEEE TNSM 13(4): 913-926, 2016.

Performance Highlights

☺

Heuristic's acceptance Ratio within 20% of optimal on avg.

* Proof is in the paper

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😐

~10% improvement in revenue/unit cost

Existing heuristic improves ~10% on revenue/cost without explicitly considering flexibility

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Summary

We make a case for having flexibility in SFC traversal order

Two Solutions to Flexible SFC Orchestration: Khaleesi, FAST-Khaleeis

Presented quantifiable benefits of flexible SFC orchestration

What's Next?

Can we exploit re-order compatibility during failure restoration/re-optimization?

What is the impact on debugging and verification?

Can we automate middlebox characterization?

Backup Slide

FAST-Khaleesi: Complexity

$$O(N^2 lgN + SN'F^2 + S(L + NlgN)))$$

N = Number of switches

N'= Number of Servers

F = Number of NFs

S = Number of possible chains
(O(F!) in the worst case)