MeshTest: End-to-End Testing for Service Mesh Traffic Management

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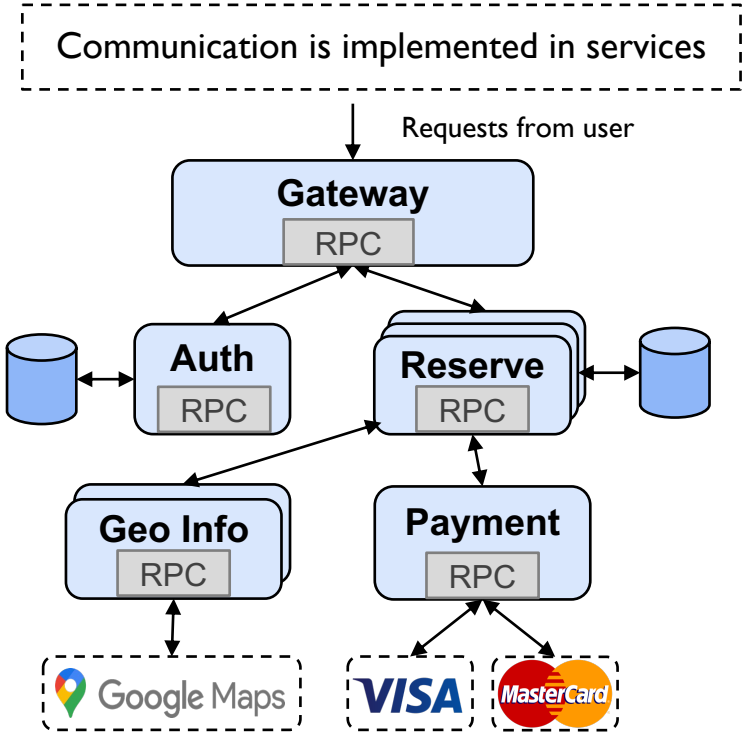
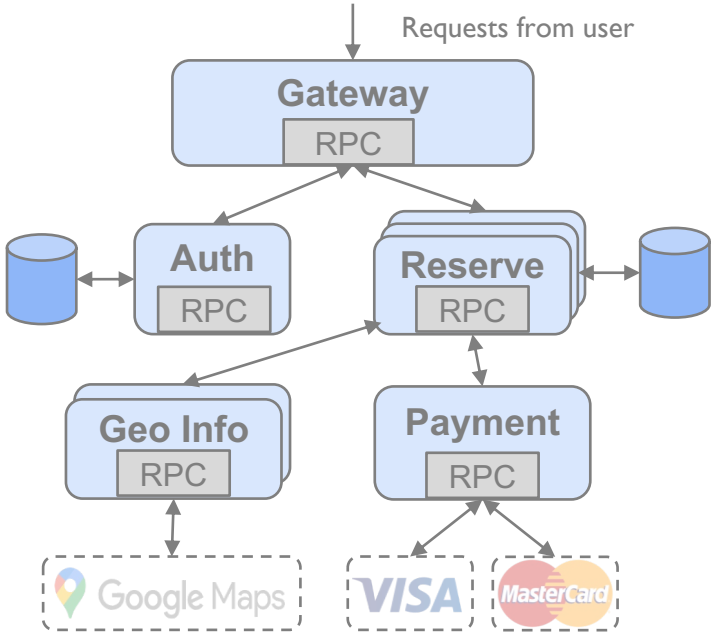
nsdi'25

Service mesh

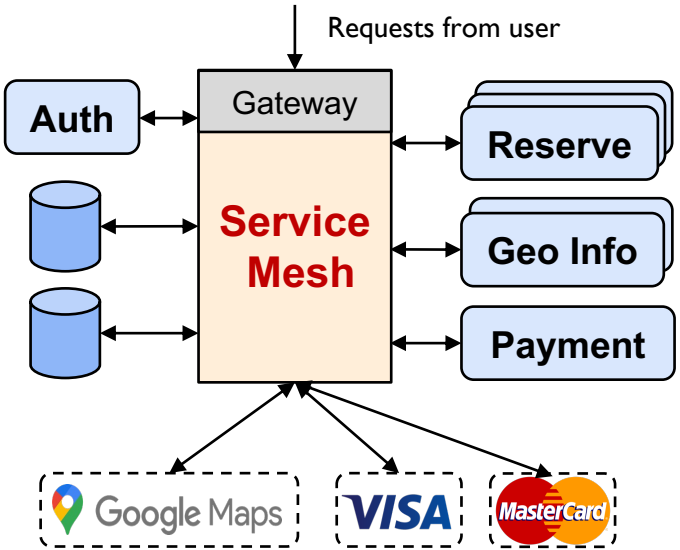


Service mesh

Communication is implemented in services



Service mesh takes over communication



Service mesh

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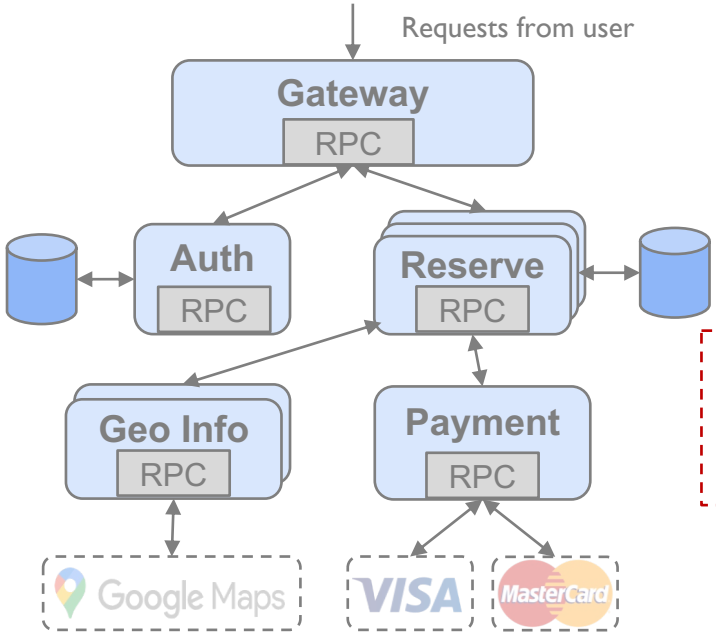
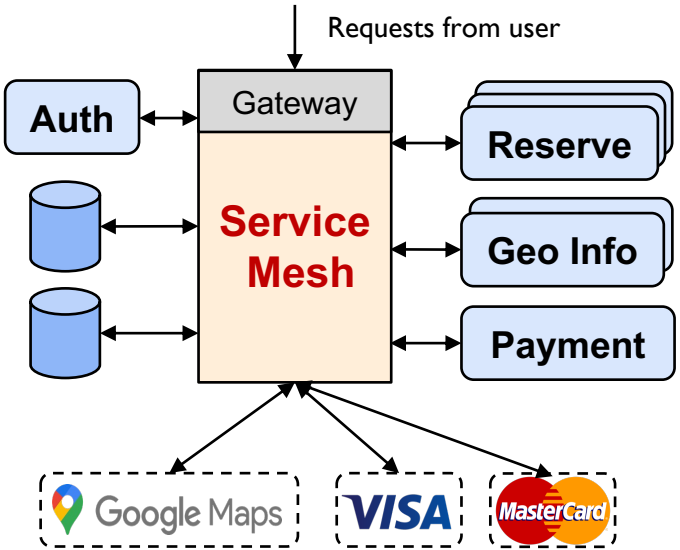


Benefits:
less maintenance costs
better reliance
better observability

Service mesh takes over communication



Service mesh

- Service mesh is the *"narrow waist"* of microservice communication

popular on GitHub

widely used by industry

integrated in clouds

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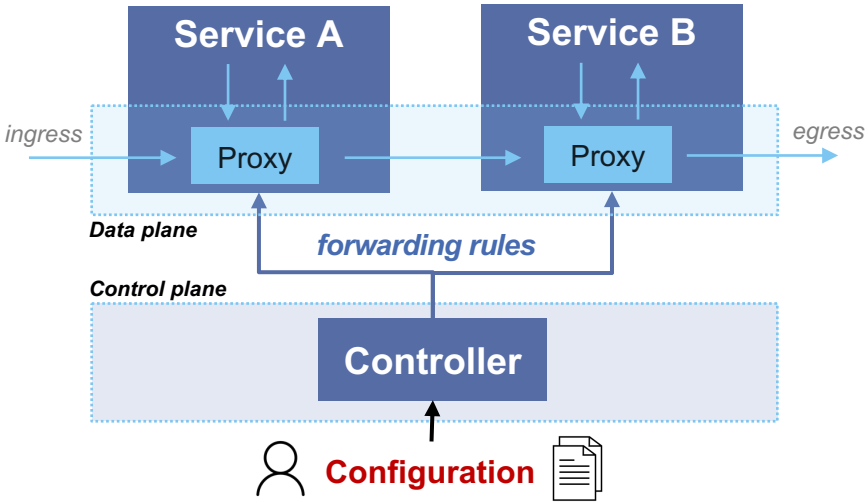
- Service mesh functionalities:
  - **Traffic Management**: service routing, load balancing, A/B testing ...
  - Authentication
  - Security
  - Observability

Service mesh is complex



Output: network behavior

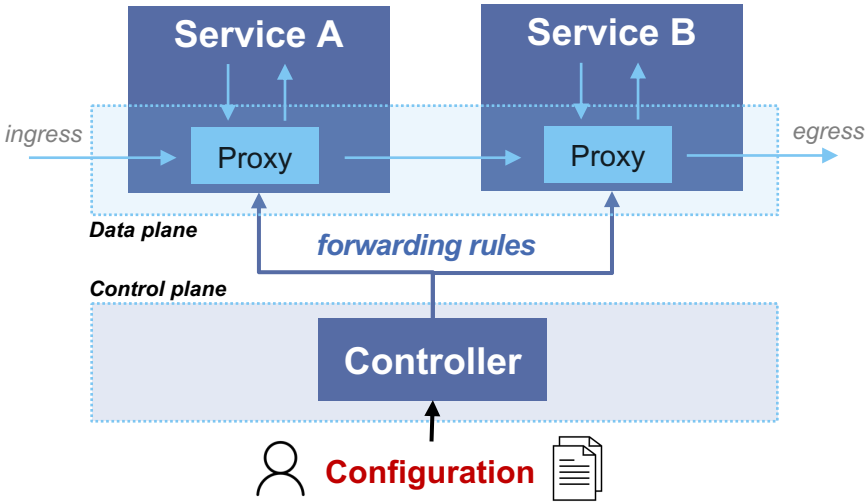
(abstract, logics for arbitrary reqeusts)

Input: communication configuration

(tens of CRDs, millions of options)

Credit to istio: https://istio.io/latest/about/service-mesh/

Service mesh is complex



Code base: extremely complex

(1,000+ components, 300,000+ lines of code)

Output: network behavior

(abstract, logics for arbitrary reqeusts)

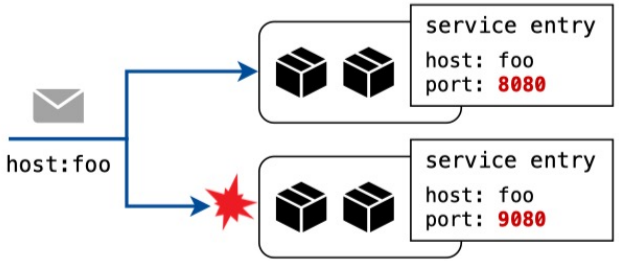
Input: communication configuration

(tens of CRDs, millions of options)

Complexity always brings bugs!

Service mesh is buggy

MeshTest



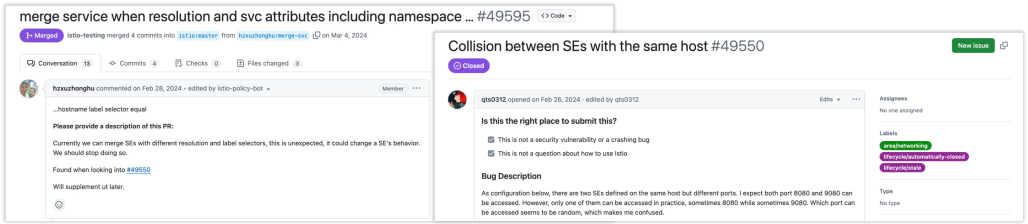
A bug found from istio by MeshTest

- Same host + different port => does not work
- Caused by incorrect rule merge in EDS

```
$ istioctl pc cluster sender-3 --fqdn "www.bookinfo.com"
SERVICE FQDN         PORT     SUBSET     DIRECTION     TYPE     DESTINATION RULE
www.bookinfo.com     8080     -          outbound      EDS
www.bookinfo.com     9080     -          outbound      EDS

$ istioctl pc endpoint sender-3 --cluster "outbound|8080||www.bookinfo.com"
ENDPOINT     STATUS     OUTLIER CHECK     CLUSTER

$ istioctl pc endpoint sender-3 --cluster "outbound|9080||www.bookinfo.com"
ENDPOINT              STATUS       OUTLIER CHECK     CLUSTER
10.244.1.90:9080      DRAINING     OK                outbound|9080||www.bookinfo.com
10.244.2.134:9080     DRAINING     OK                outbound|9080||www.bookinfo.com
```



Reported in https://github.com/istio/istio/issues/49550

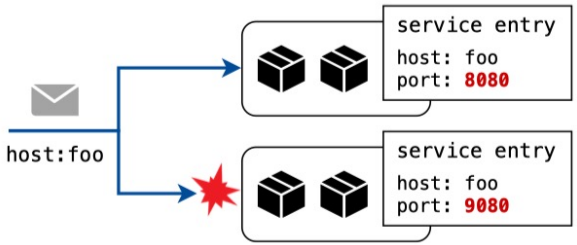
Fixed in https://github.com/istio/istio/pull/49595

Existing tests are not sufficient

- Existing tests
  - A lot of unit tests
    (Istio has 10,000+ unit tests)
  - Very few end-to-end tests
    (Istio has 160 e2e tests, Linkerd has 30 e2e tests)

Existing tests are not sufficient

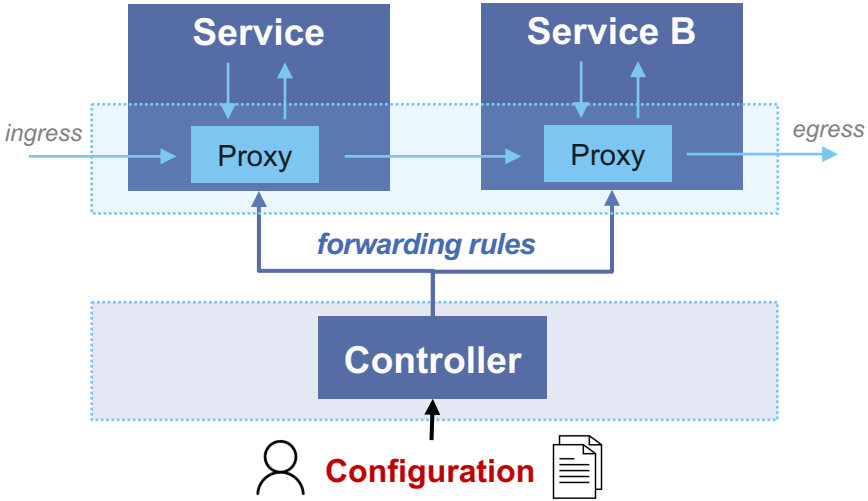
- Existing tests
  - A lot of unit tests
    (Istio has 10,000+ unit tests)
  - Very few end-to-end tests
    (Istio has 160 e2e tests, Linkerd has 30 e2e tests)
- End-to-end testing is effective for the interactions between functions



- Simple in end-to-end testing
- Difficult for unit testing
  Since it is caused by rule merging between two functions

End-to-end testing is challenging

MeshTest



Input

- configurations describing network functions

Output

- network behaviors for requests

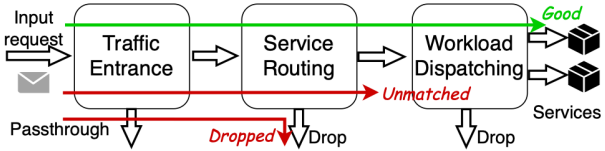
Two steps testing

- Step 1: service mesh configuration generation
- Step 2: network behavior checking

End-to-end testing is challenging

Challenge 1:

The input configurations must be *end-to-end effective*




```
Kind: VirtualService          Kind: DestinationRule
Route:                        Host: example.com
  Host: example.com           Subset:
  Subset: v1 ---------------> v1: workload-1
          v2 ---------------> ✸
```

end-to-end path

broken path (subset:v2 not defined)

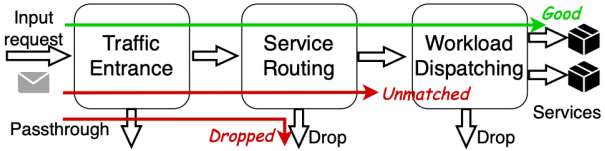
If all requests cannot go to egress service, the input is NOT end-to-end effective.

End-to-end testing is challenging

MeshTest

Challenge 1:

The input configurations must be *end-to-end effective*

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end-to-end path

broken path (subset:v2 not defined)

If all requests cannot go to egress service, the input is NOT end-to-end effective.

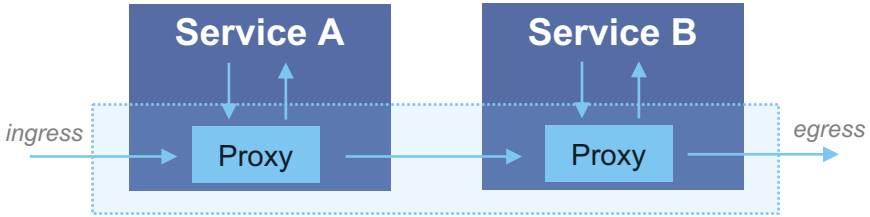
- The configuration must orchestrate functions to compose end-to-end service flow paths
- Each function needs to pass validation rules

- Symbolic execution?
  - 1 million+ options explodes
- Fuzzing?
  - challenging to compose e2e service flow paths
  - not easy to pass constraint validation

End-to-end testing is challenging

Challenge 2:

The output correctness cannot be directly judged

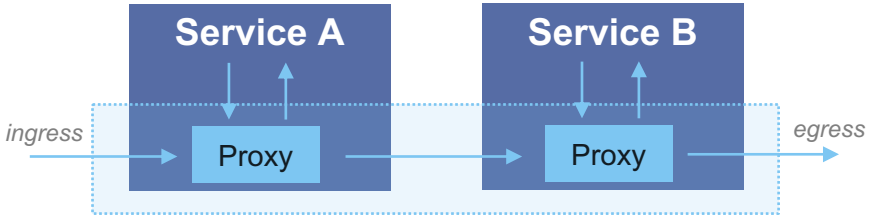


- Correct network behavior means that the service mesh can correctly process any requests
- One request is handled correctly does not mean that all requests will be handled correctly.

End-to-end testing is challenging

Challenge 2:

The output correctness cannot be directly judged



- Correct network behavior means that the service mesh can correctly process any requests
- One request is handled correctly does not mean that all requests will be handled correctly

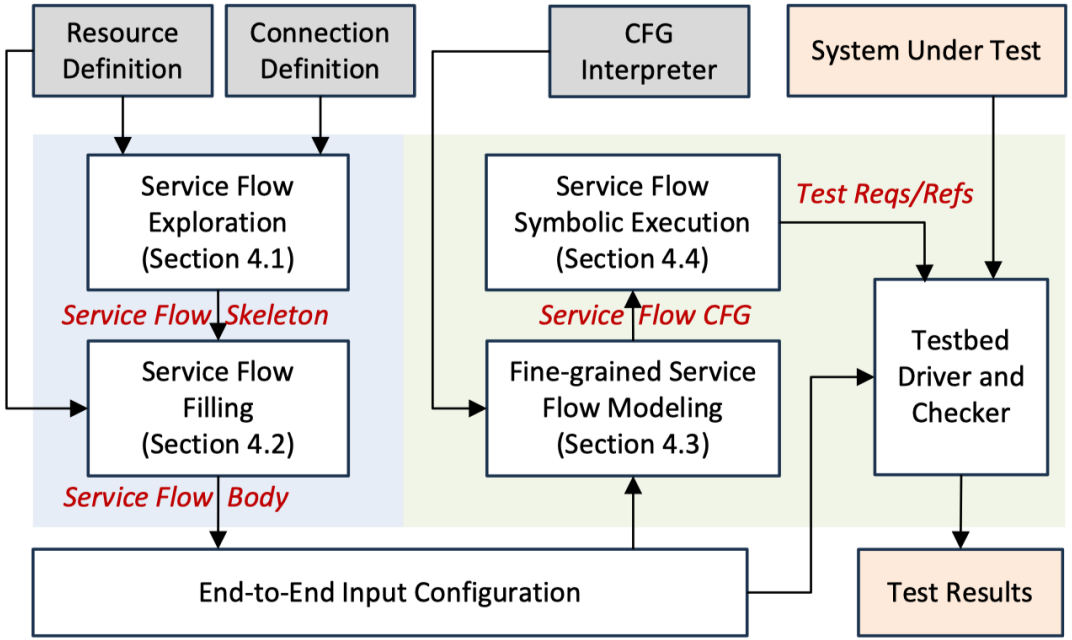
We need to ...

- Choose a comprehensive set of requests that is capable to represent all requests
- Infer the correct processing behaviors of each representative request

The checker should be automatic

MeshTest: end-to-end testing service mesh

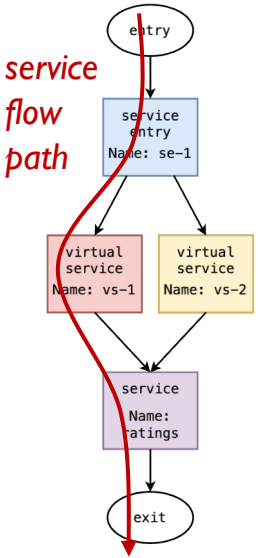
End-to-end configuration generation



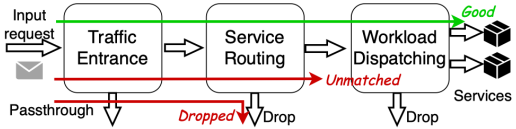
Automatic service mesh oracle checking

Stage 1: service flow exploration

- We start from service flows – the key of end-to-end input configuration



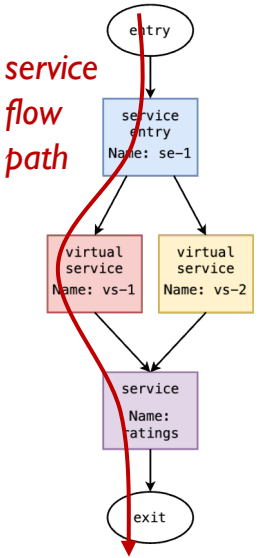
Goal: create e2e service flows



- Domain specific service flow skeleton abstraction
  - Which resources are used in the configuration
  - How resources transmit requests for service flow
- Skeletons reveal interactions between resources
  - priority competition
  - request handover

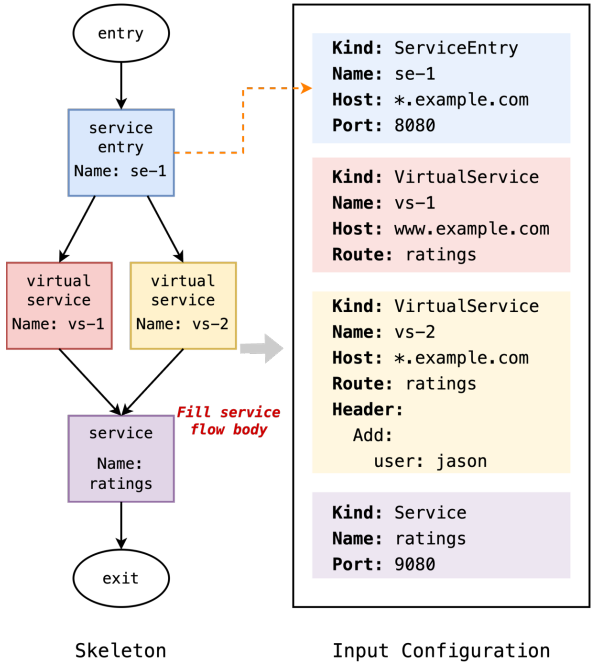
Stage 1: service flow exploration

Goal: create e2e service flows → Goal: create various skeletons



- Insight: vulnerable resource interactions
- Generate skeletons to cover all resource interactions
- Details
  - Start from interaction seed
  - Extend to entry and exit side
  - Compose complete service flow skeleton
- Open to other heuristic seeds

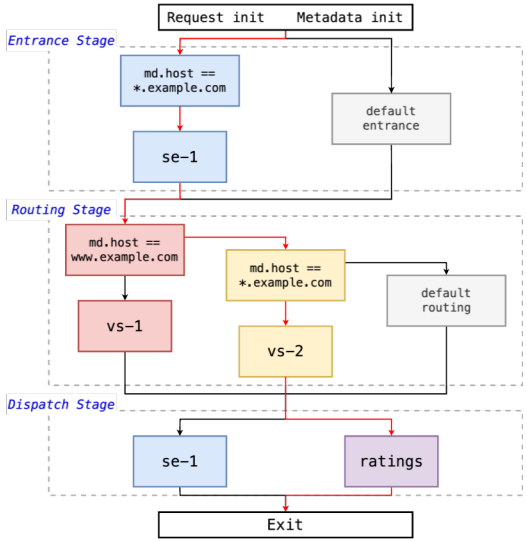
Stage 2: service flow filling



Goal: transform skeleton into complete configuration

- Fill connector fields to realize resource interactions
- Extend configurations with more options
  - by constraint based fuzzing
- More details in out paper...

Stage 3: fine-grained model



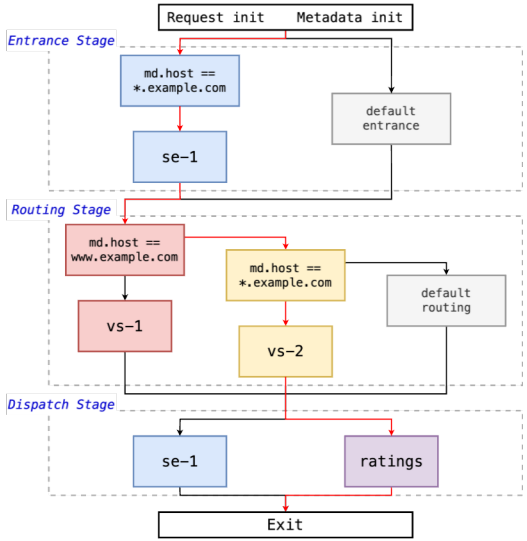
CFG

Goal: select a comprehensive set of requests to check

- Input generator: stage 1 + stage 2
- Oracle: check whether service mesh realizes input configuration correctly

- Stage 3 models accurate behaviors with CFG
- Each path represents a unique request

Stage 3: fine-grained model



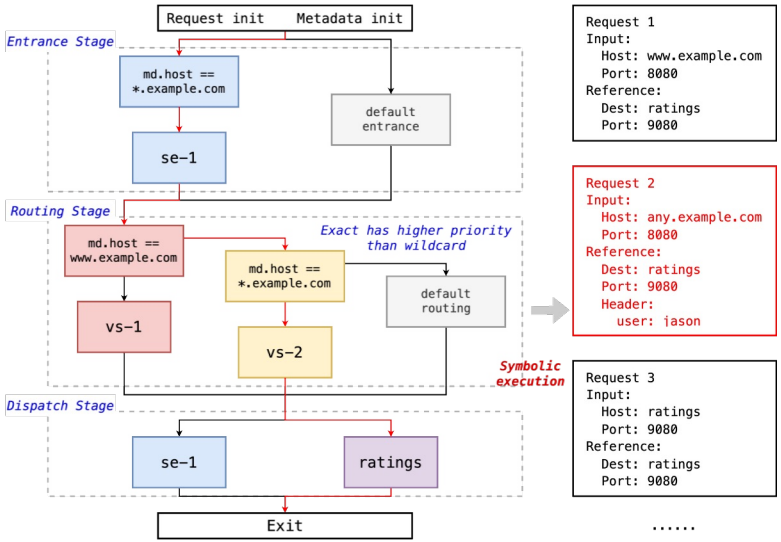
CFG

Goal: select a comprehensive set of requests to check

- Automatic interpreters: configuration => CFG
- The retrofitting effort is less than 2 person-weeks

- We built interpreters for istio and linkerd
- We provide MeshTest CFG APIs for other systems

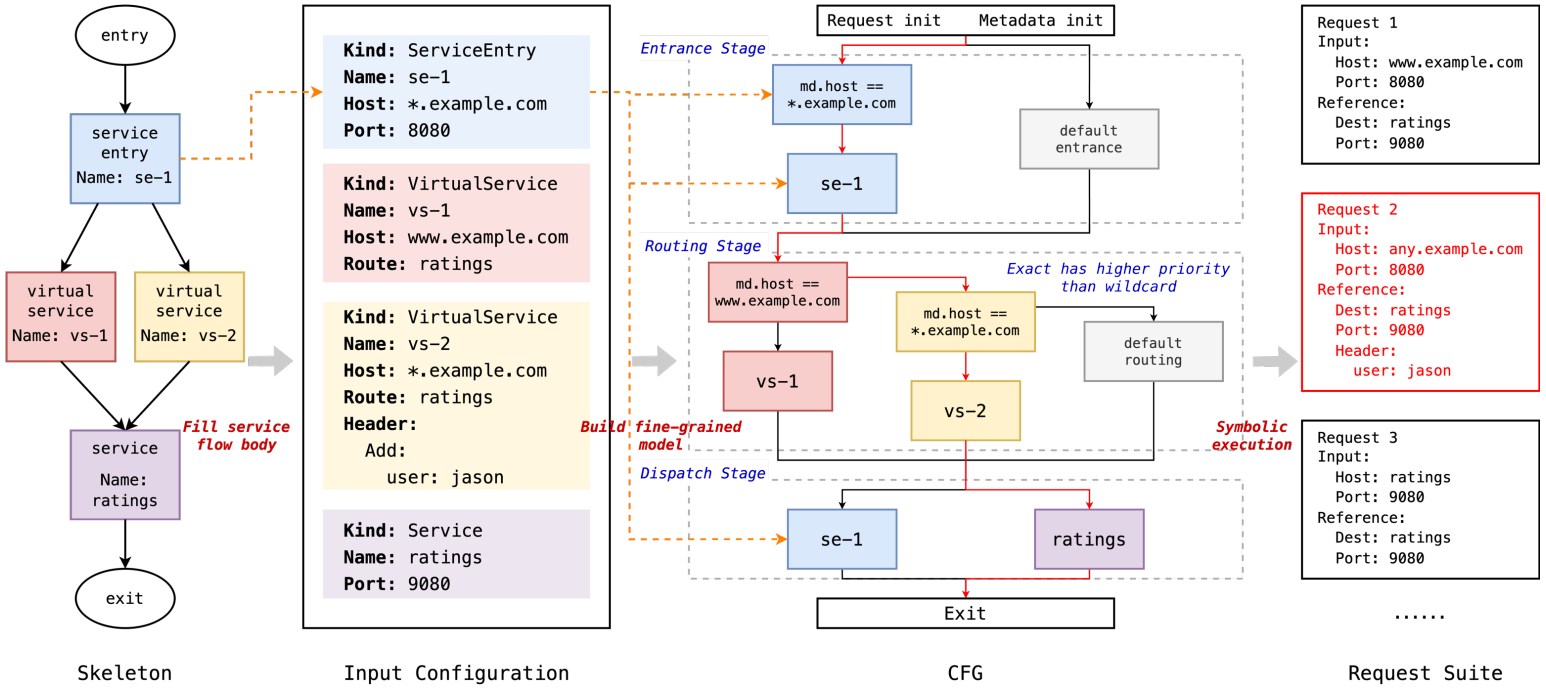
Stage 4: symbolic execution



Goal: check result of requests

- Symbolic execution on CFG
  - solves ingress and reference egress
- Test driver
  - check actual ?= reference
- Properties
  - liveness: no panic or error
  - correctness: consistent with CFG model

MeshTest workflow



Evaluation

Index	Implementation	Bug Description	Status
1 [18]	Istio 1.19–1.21	Empty prefix in specific fields causes an internal error	Fixed
2 [19]	Istio 1.19–1.21/dev	Port 80 is not open by default when Istio gateways are not installed	Reported
3 [20]	Istio 1.19–1.21/dev	Traffic passthroughs cluster when `service entry endpoints` set to an internal IP	Reported
4 [21]	Istio 1.19–1.21/dev	`Service entry` with wildcard host makes traffic skip service routing	Confirmed
5 [22]	Istio 1.19–1.21/dev	`Service entry` defined on port 80 disables `virtual service`	Confirmed
6 [23]	Istio 1.22dev	Routing fails under multiple interleaved resources	Fixed
7 [24]	Istio 1.19–1.21/dev	Traffic is not dropped when port not matched in `virtual service`	Confirmed
8 [25]	Istio 1.19–1.21	`WithoutHeaders` matching fails without target header	Fixed
9 [26]	Istio 1.19–1.21	Delegation influences the priority between `virtual services`	Fixed
10 [27]	Istio 1.19–1.21/dev	Match conditions influence the choice of `virtual service` for gateway	Confirmed
11 [28]	Istio 1.19–1.21/dev	`Service` defined on port 80 disables `virtual service`	Reported
12 [29]	Istio 1.19–1.21	Update on `targetPort` does not trigger update on `EDS`	Fixed
13 [30]	Istio 1.19–1.21/dev	Wildcard matching fails on destination host	Reported
14 [10]	Istio 1.19–1.21	Collision between `service entries` with same host but different workloads	Fixed
15 [31]	Istio 1.19–1.21/dev	`EDS` missing for `service entry` defined on the same host as `service`	Confirmed
16 [32]	Istio 1.19–1.21/dev	`WorkloadSelector` takes effect at wrong place	Confirmed
17 [33]	Istio 1.19–1.21/dev	Header manipulation fails when the value is empty string	Confirmed
18 [34]	Istio 1.19–1.21/dev	Special headers are not ignored in match conditions	Confirmed
19 [35]	Istio 1.19/1.20	Header manipulation fails on pseudo headers	Fixed
20 [36]	Linkerd 2.14	Linkerd extension drives specific pods crash	Fixed
21 [37]	Linkerd 2.14	Routing error under rules with the same matching conditions	Fixed
22 [38]	Linkerd 2.14	Routing error under `http routes` bound on the same `gateway`	Fixed
23 [39]	Linkerd 2.14/dev	Incorrect `hostnames` effects	Confirmed

	Istio	Linkerd	Total
Entrance error	1	0	1
Routing error	9	3	12
Dispatching error	5	0	5
Internal error	1	1	2
Others	3	0	3
Total	19	4	23

MeshTest has found

23 new bugs

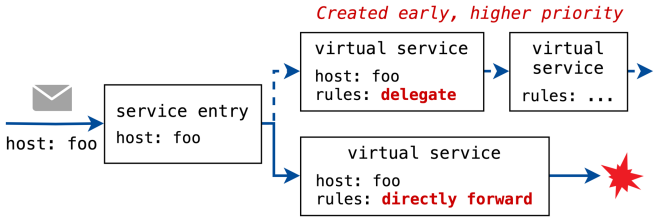
19 confirmed

10 fixed

Evaluation

- Testing coverage
  - 100% coverage on functionalities specified in pairwise resource interactions
  - Istio TM overall: 74.1% (w/o MeshTest) => 78.8% (w/ MeshTest)
  - Istio interaction overall: 70.9% (w/o MeshTest) => 79.4% (w/ MeshTest)
- Efficiency:
  - 2500 configurations per second (input generator)
  - 29 different requests to check one configuration (oracle)

A real bug found by MeshTest



- curl foo/api returns 404 error
- The bug occurs when:
  1. two resources with same host but different rules
  2. higher priority one has a delegation rule

MeshTest found this bug by:

1. generating configuration containing the interaction
2. creating a real request hitting the rule
3. detecting difference between actual and reference

Conclusion

- MeshTest is the first automatic end-to-end testing framework for traffic management of service mesh
- MeshTest is composed by
  - an end-to-end input generator for service mesh
  - a service mesh oracle based on symbolic execution
  - they can work seperately!
- MeshTest has found 23 new bugs (19 confirmed, 10 fixed)
- Available at https://github.com/pkusys/meshtest/

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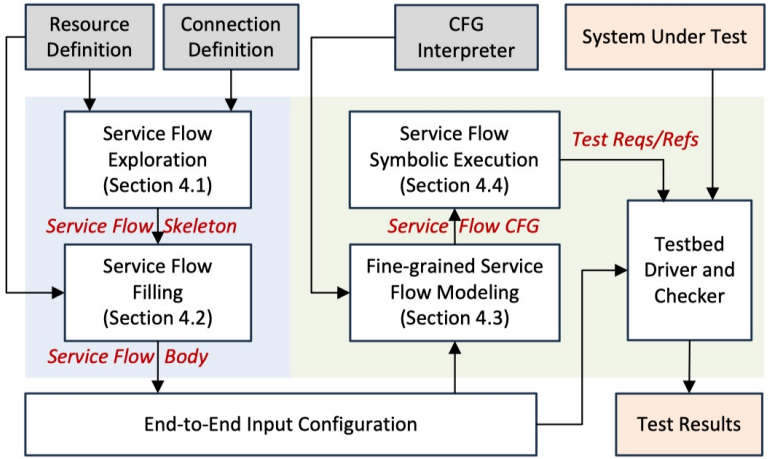

Thanks!

Naiqian Zheng

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