# Securing Workflows

## On the Use of Microservices and Metagraphs to Prevent Data Exposures


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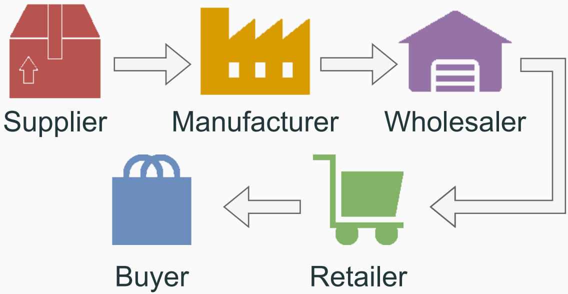
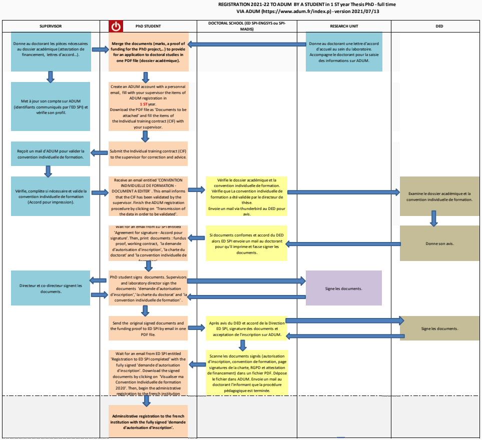
# Businesses and operations

Workflows are used **everywhere** and by **everyone**.



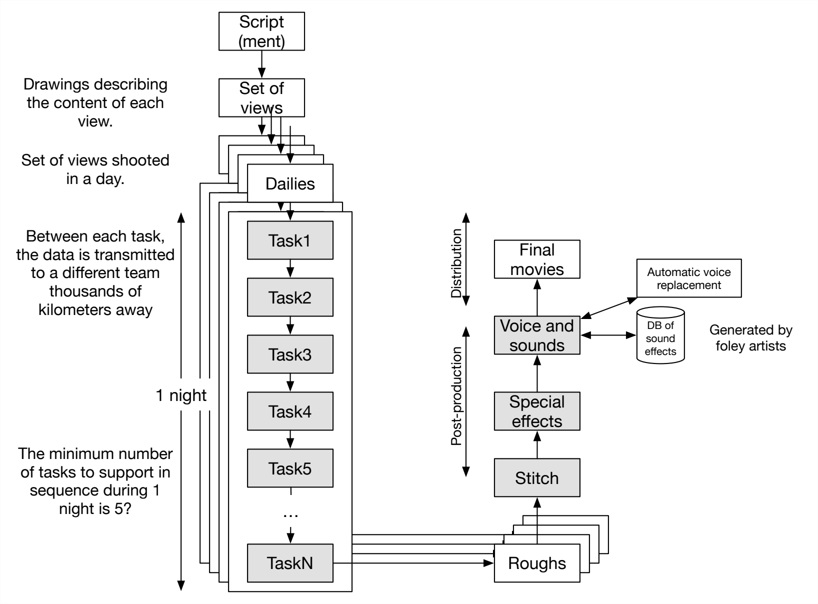

Supply chain, customer orders, ticketing systems, etc.

# Businesses and operations - Sometimes convoluted



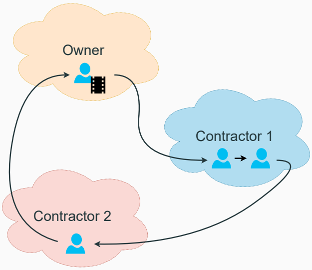

They can be complex.

# Businesses and operations - Sometimes straightforward



## Workflows

- **Sequence of tasks** processing a set of data.



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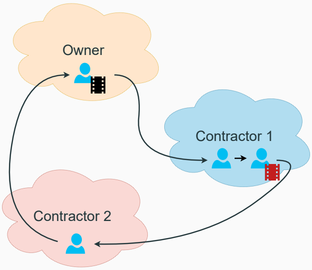

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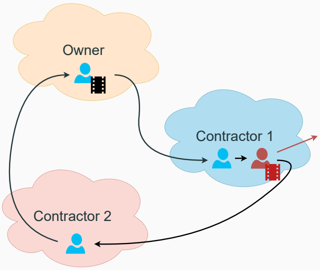

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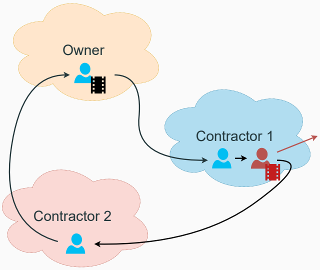
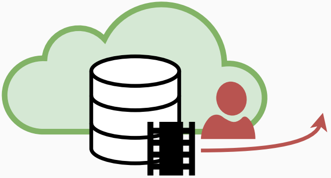



In the movie industry, data is often stored **unencrypted** in the cloud.

# Data exposures

**Sensitive data** is accessed by an **unauthorized party**.

Breach



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**Exploit** flaws in the security of the system.

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- 2013 Yahoo data theft.
- **88%** of cloud breaches due to **human error**.

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Leak due to **processing**.

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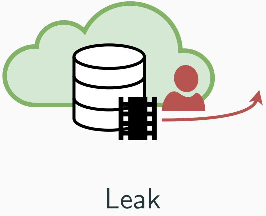


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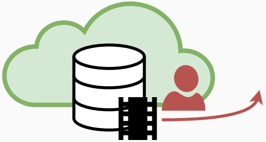

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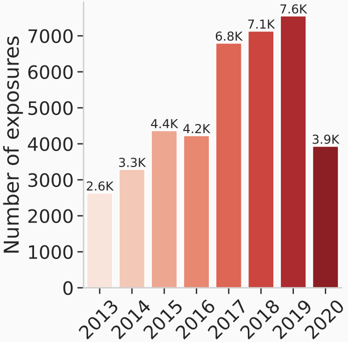


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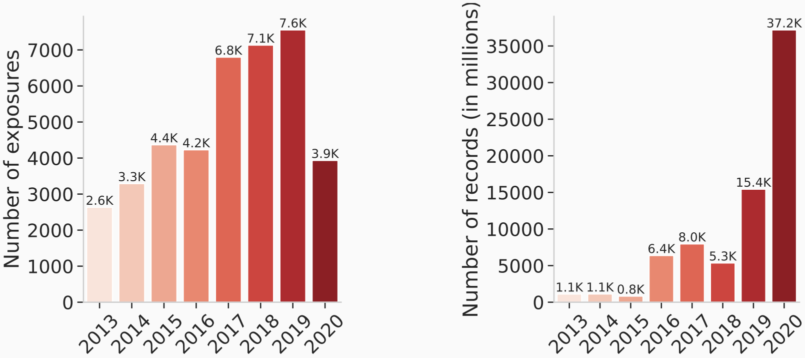


Record = **collection** of related fields.

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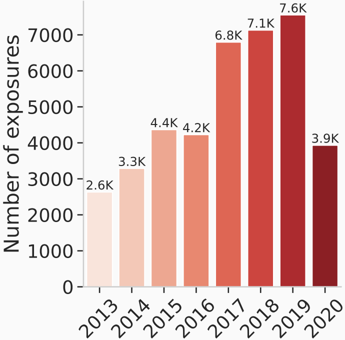


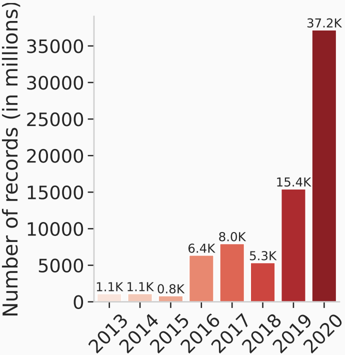


**82%** of compromised records from **five leaks.**

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# Overview

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2. Exposures are **widespread**, outcomes of **critical** vulnerabilities, and happening **more**.
3. The shift to the cloud has brought **new security risks**.

# Research statement

**Enforce secure multi-party workflows and prevent data exposures**

# Research questions

- **RQ1:** How can we use microservices to enable multi-party workflow?

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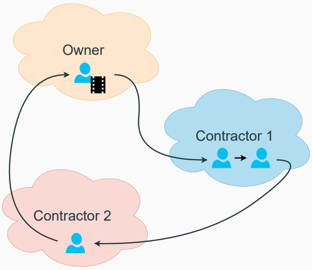
- **RQ2:** How do we verify a policy specification corresponds to its implementation?
- **RQ3:** How do we verify a policy specification contains no redundancies?

# A Secure Infrastructure to Prevent Data Exposures

# Workflows

- Workflow is a **sequence of tasks** processed by a set of actors.
- **Owner** of the data interacts with **contractors** to realize task.
- Actors have **agents**: employee or automated service.

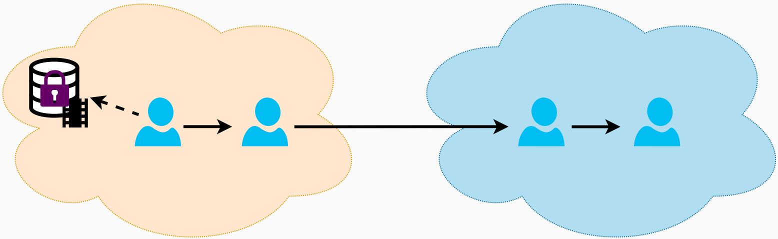


# Objectives

**How can we enforce workflows and prevent data exposures?**

# Achieved properties

- Data security **at rest**: stored **encrypted**,



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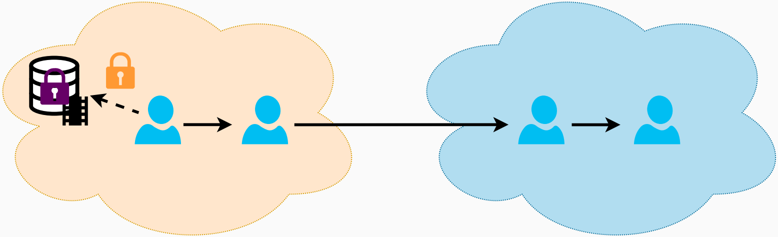

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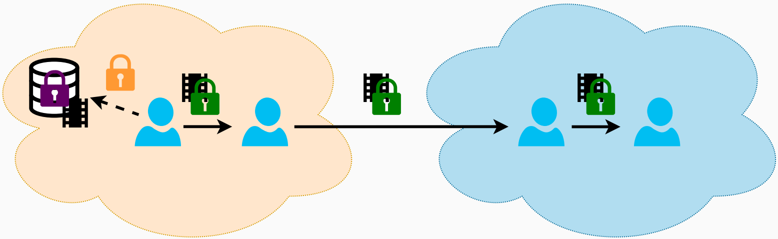

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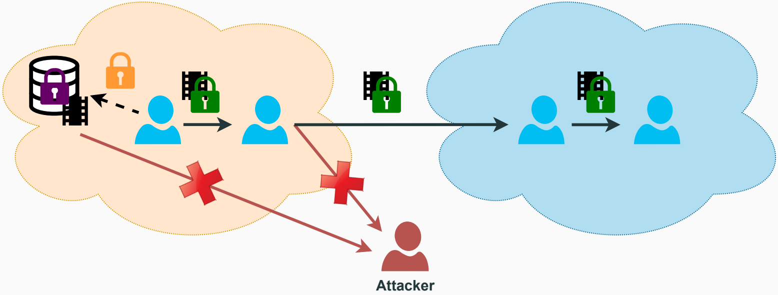
The data cannot be **leaked** in both cases.

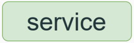
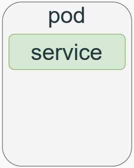


# Building block security properties

| Service |
| --- |
| service |
| Isolation |

Encrypted storage, encrypted communications, policy enforcement.

# Building block security properties

| Service | Orchestrator |
|---|---|
|  |  |
| Isolation | Isolation |
| | Encryption (at rest) |

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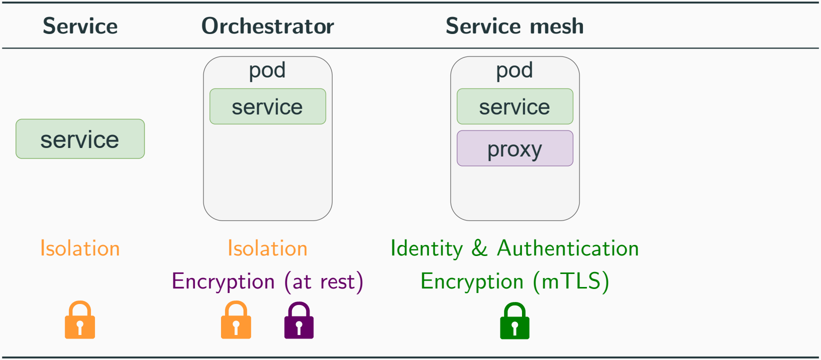


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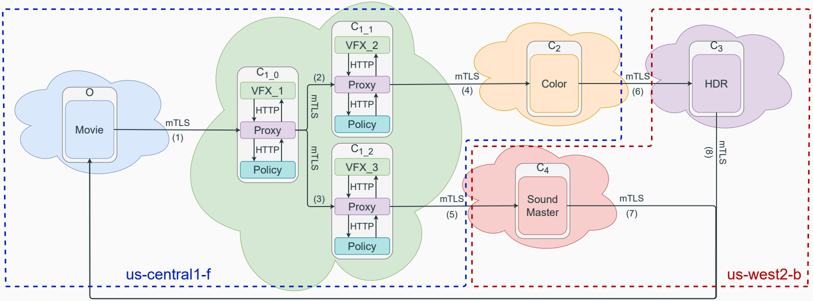
# Building block security properties

| Service | Orchestrator | Service mesh | Policy engine |
|---|---|---|---|
| service | pod: service | pod: service, proxy | pod: service, proxy, policy |
| Isolation | Isolation<br>Encryption (at rest) | Identity & Authentication<br>Encryption (mTLS) | Authorization |

Encrypted storage, encrypted communications, policy enforcement.

# Proof of Concept deployed on Google Cloud Platform

Post-production movie workflow.




- One Kubernetes cluster per actor.
- One n1-standard-v2 per cluster (2 vCPUs, 7.5 GB of memory), except the owner which has two.

# Evaluating security overhead

Pod startup time and Request duration.

# Effect of policy engine on pod startup time

- Independent-samples t-test
- Two deployments: one with policy engine and one without.
- 130 observations per pod ($N = 1820$).

Time increased by **2 seconds on average (32.72%)**.

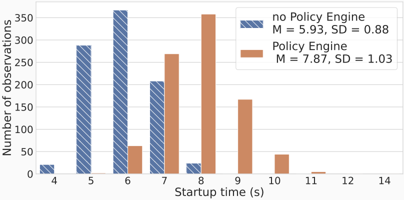
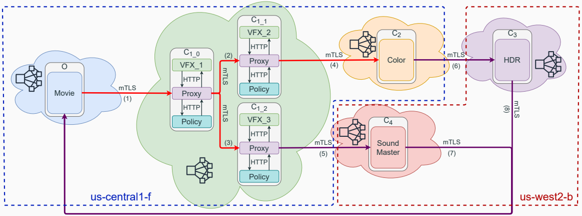


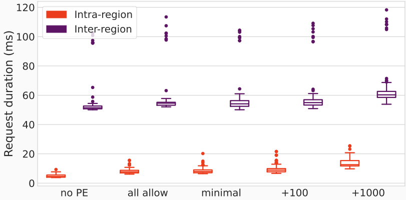

**Figure 1:** Startup time distribution

# Effect of policy size on request duration




We analyze **intra-region** and **inter-region** communications.

- +5 – 10ms on average.
- Low impact inter-region.



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- Performance analysis: Acceptable tradeoff.

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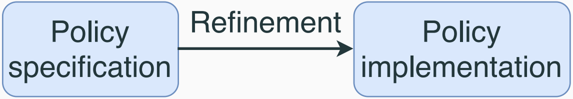
# Motivation

**Access Control** is an essential building block of security. Generally managed by a policy administrator.



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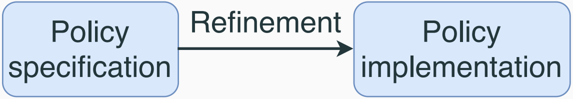


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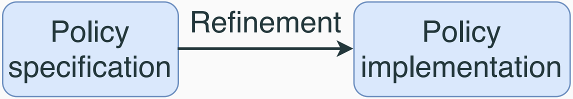


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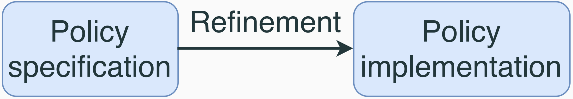


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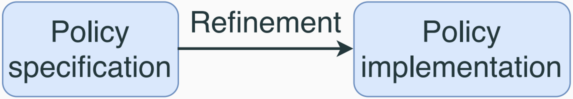



**Prone to errors**:

- Attackers.
- Distributed deployments.
- Refinement: Semi-automatic or automatic tools.

## Objective: Policy verification

- Verify the implementation matches the specification
- Pinpoint errors

## Why metagraphs?

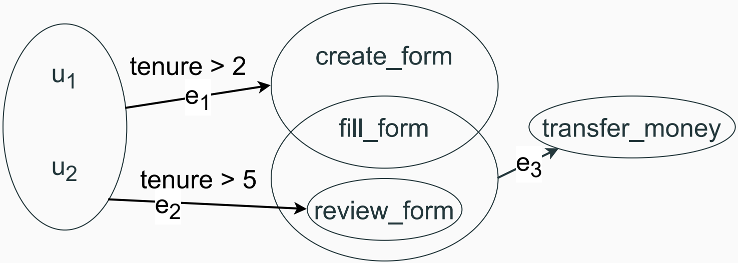
- Existing works dealing with policy verification use SAT solvers [2], decision diagrams [3] or graphs [10].

| | SAT solvers | Decision diagrams | Graphs | Metagraphs |
|---|---|---|---|---|
| Natural policy modeling | ■ | ◪ | ◪ | ■ |
| Visual representation | □ | ◪ | ◪ | ■ |

- Properties **specific to metagraphs** for detecting conflicts and redundancies[4].

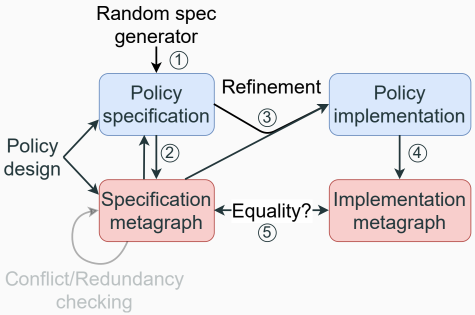
[4] Dinesha Ranathunga, Matthew Roughan, and Hung Nguyen. “Verifiable Policy-Defined Networking using Metagraphs”. In: *IEEE Transactions on Dependable and Secure Computing* (2020).

# The metagraph: a collection of directed set-to-set mappings [1]




Employees ($u_1$, $u_2$) and tasks (*create_form*, *fill_form*, *review_form*, *transfer_money*) are put into relation by the edges ($e_1, e_2, e_3$) between sets of elements.

# Policy verification procedure




Tools

① RandomWorkflowSpecGenerator
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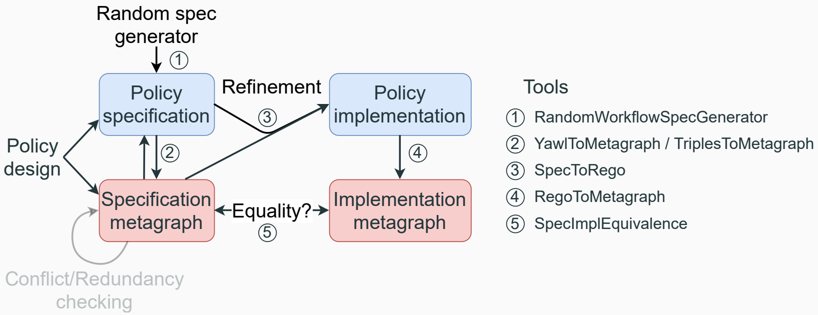


Policy specification: YAWL, or metagraph-like format.

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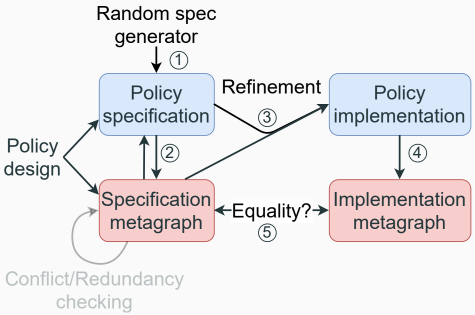


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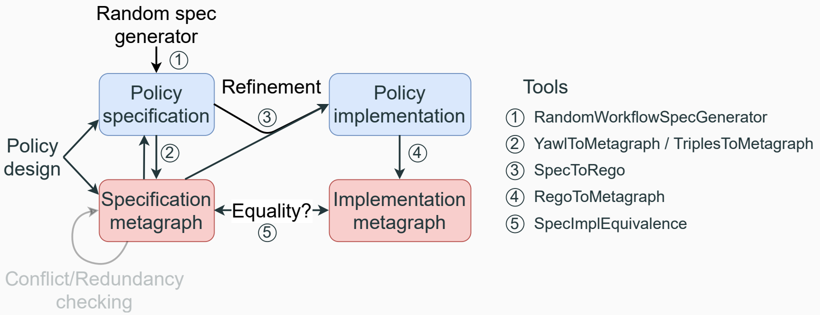


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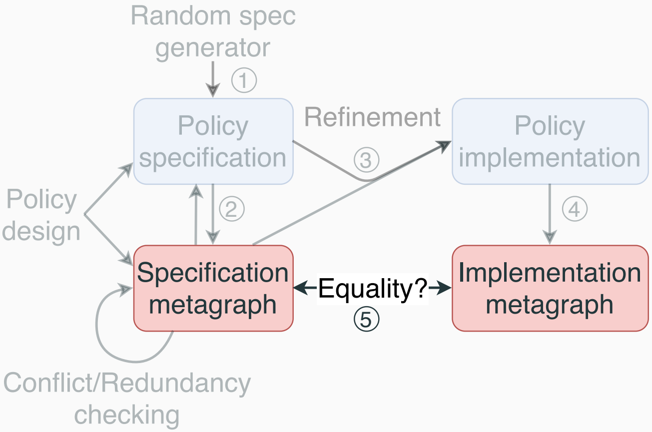
We can pinpoint errors in the policy.

## Performance analysis ⑤



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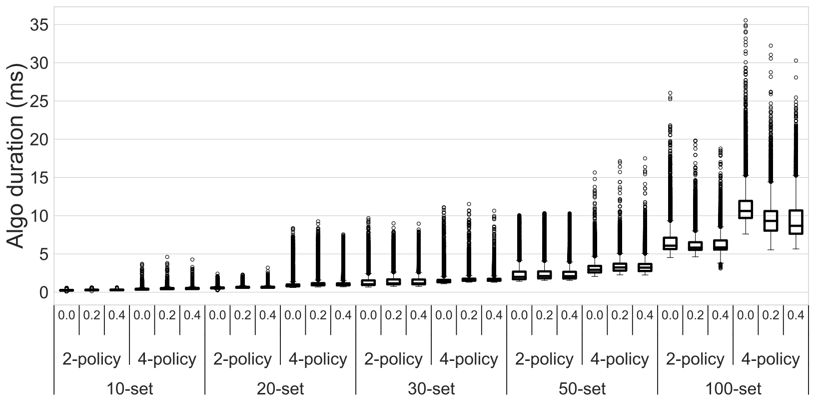
Rego policy files between 305 and 24729 lines of code, **in line** with observed policies.

# Time increases with number of elements and policy size




- Verification times between 0 and 12 ms on average.
- Error rate has a negligible effect (correlation of 0.01).

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- Evaluated our method: verification times **between 0 and 12 ms** on average.

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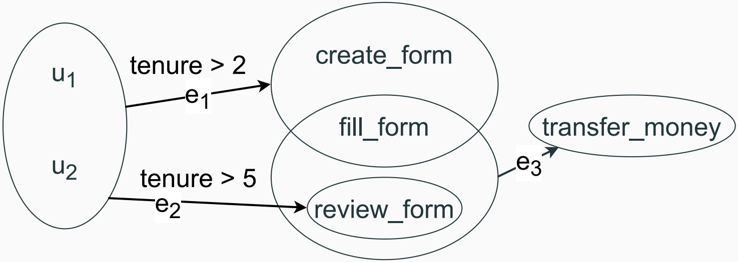
...but the current solution has shortcomings.

# Metapaths are not simple paths




$M_1(\{u_1, u_2\}, \{transfer\_money\}) = \{e_1, e_2, e_3\}$ is a **metapath**.

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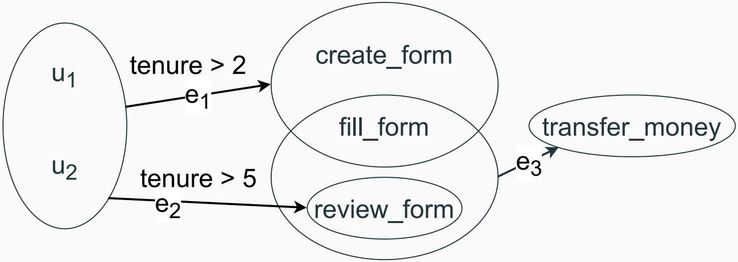
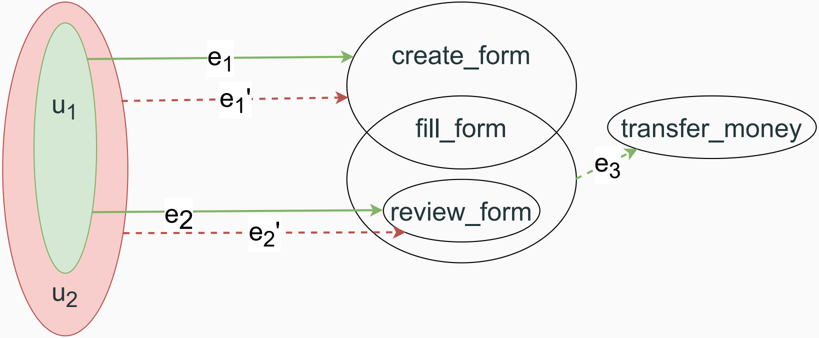



$M_1(\{u_1, u_2\}, \{transfer\_money\}) = \{e_1, e_2, e_3\}$ is a **metapath**.

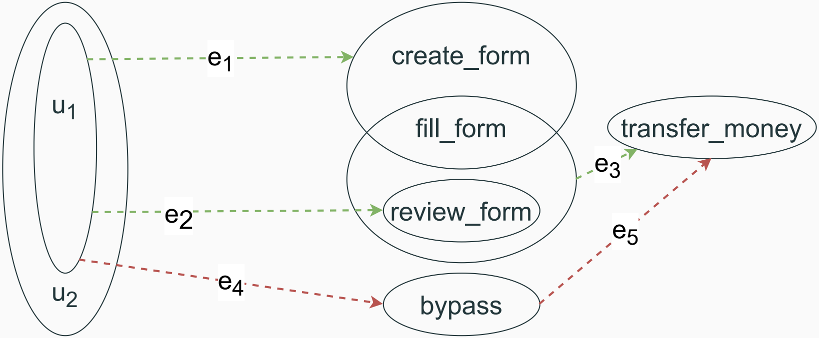
A metapath is **dominant** if it is both **input-dominant** and **edge-dominant**.

# Input dominance - Minimality of input




$M_1(\{u_1, u_2\}, \{transfer\_money\}) = \{e_1', e_2', e_3\}$ is not input-dominant because $M_2(\{u_1\}, \{transfer\_money\}) = \{e_1, e_2, e_3\}$ is a metapath.

## Edge dominance - Minimality of edges




$M_1(\{u_1\}, \{transfer\_money\}) = \{e_1, e_2, e_3, e_4, e_5\}$ is not edge-dominant because $M_2(\{u_1\}, \{transfer\_money\}) = \{e_1, e_2, e_3\}$ is a metapath.

# Dominant metapaths identify minimal access.

Elements not on any dominant metapath are redundant.

Rationale: In every possible access, we can do without the redundancy.

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> *"...simply check all feasible metapaths in a policy metagraph for edge and input dominance, if either fails, the policy includes redundancies" - Ranathunga et al. [9].*

Great! Problem solved, right?

## In reality...

- Checking all metapaths takes too much time.

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- Even worse, just finding all metapaths takes too much time.

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Implementing their method, it took **1 hour** to process metagraphs of **13 elements at most**.

# Alternatives?

- No simple algorithm.
- Can it be done?
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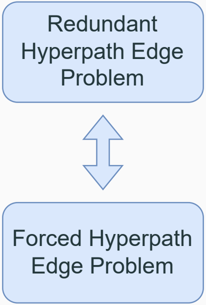
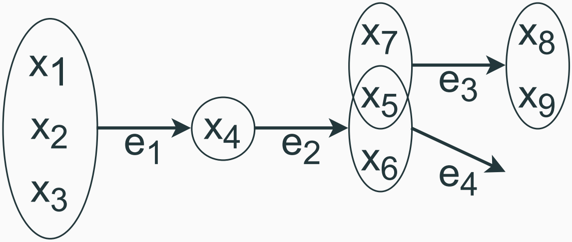
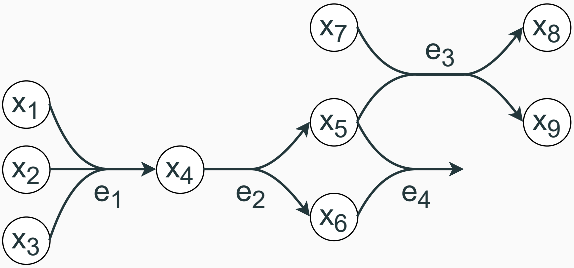
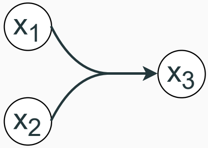


# Hypergraphs, a structure related to metagraphs.

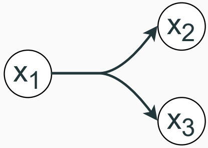


# Types of hypergraphs (B, F, BF)




B-edge




F-edge

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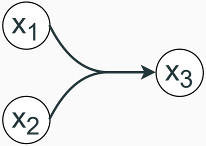


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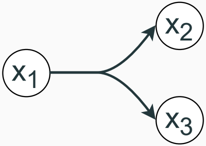


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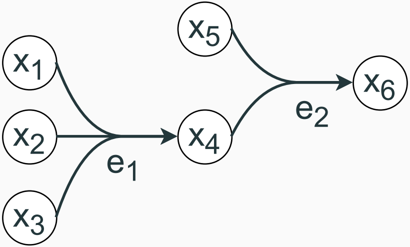


B-hypergraph

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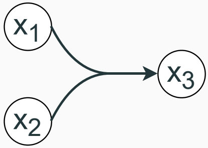


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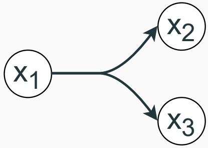


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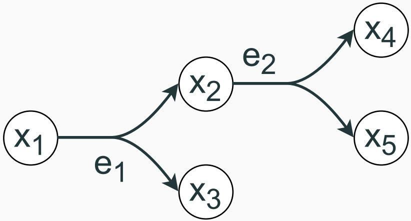


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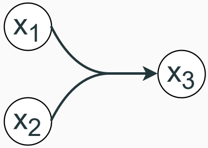


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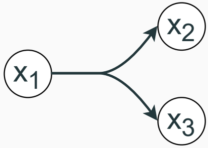
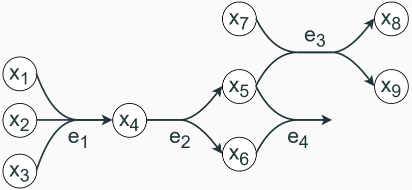
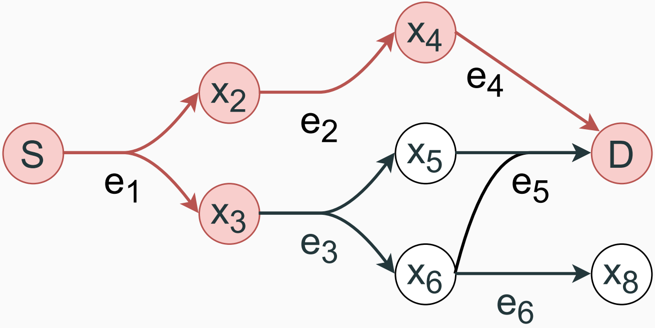



F-edge



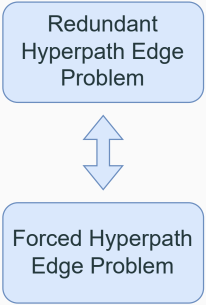

BF-hypergraph

# Hyperpaths




- Minimal sub-hypergraph $\mathcal{H}'$.
- Invertex of new edge must already be in hyperpath.

# Proof that finding redundancies is NP-Hard



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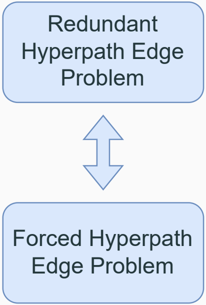
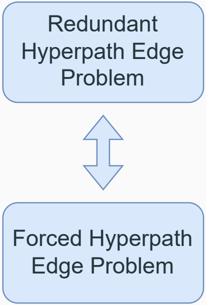



- Find all redundant edges in $\mathcal{H}$.

## Proof that finding redundancies is NP-Hard

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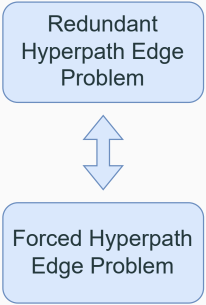


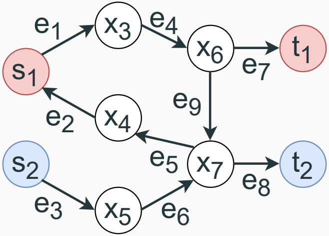

- Find all redundant edges in $\mathcal{H}$.
- Is there an input-dominant hyperpath in $\mathcal{H}$ using $e$.

An input-dominant hyperpath using $e$ means $e$ is not redundant.

# Proving the FHEP is NP-Complete with simple graphs

The **Forced Path Edge Problem**: simple graph version of the FHEP.

Reduction from **2-VDPP**, a known NP-Hard problem.



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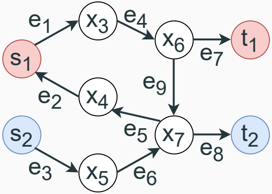
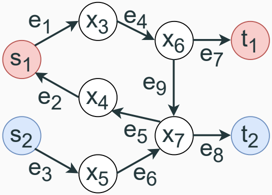



Disjoint paths (2-VDPP)

Suppose we have an instance of 2-VDPP.

# Proving the FHEP is NP-Complete with simple graphs

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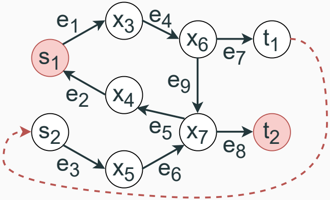
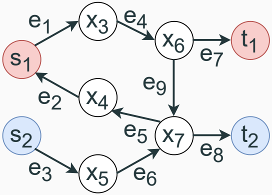



$G'$ construction (FPEP)

**Construction** $G'$ with added forced edge.

# Proving the FHEP is NP-Complete with simple graphs

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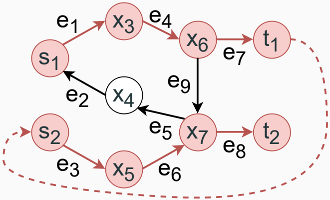
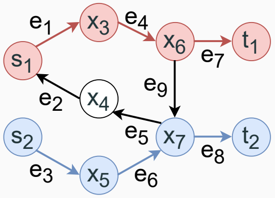



$G'$ construction (FPEP)

A solution to FPEP is a simple path from $s_1$ to $t_2$ via $e'$.

# Proving the FHEP is NP-Complete with simple graphs

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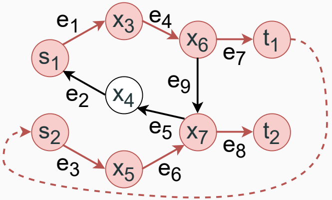


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A solution to FPEP is a solution to 2-VDPP.

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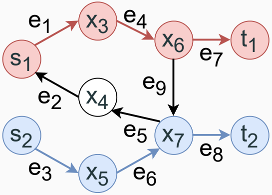


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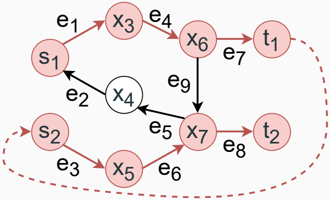
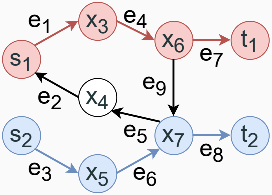



$G'$ construction (FPEP)

**The Forced Path Edge Problem is NP-Complete.**

# Proving the FHEP is NP-Complete with simple graphs

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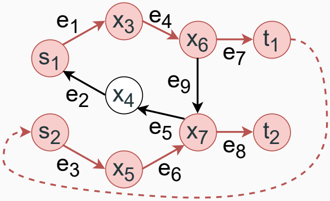


$G'$ construction (FPEP)

**The Forced Path Edge Problem is NP-Complete.**

**Corollary: the FHEP is NP-Complete.**

## Complexity summary

| | | | Redundancy |
|---|---|---|---|
| Forced Edge | Cyclic | B | NP-Hard [13] |
| | | F | NP-Hard [13] |
| | | BF | NP-Hard [13] |
| | Acyclic | B | P (linear) [13] |
| | | F | ? |
| | | BF | ? |

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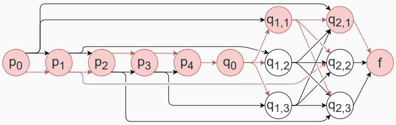
| | | F | NP-Hard [8] |
| | | BF | NP-Hard [8] |

# Acyclic F-hypergraph proof

Reduction from 3-SAT.

$$(v_1 \vee v_2 \vee \neg v_4) \wedge$$
$$(v_1 \vee \neg v_2 \vee \neg v_3)$$

3-SAT instance




Our construction.

The FHEP in an acyclic F-hypergraph is NP-Complete.

## Trying to get a correct result faster

- Correct result by enumeration (1 hour / 6 elements).

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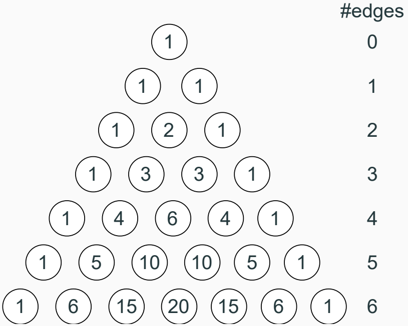
What aspects of metapaths can we exploit to be faster?

**Dominance!**

- We only need **dominant metapaths** to compute the solution, not all of them.
- A dominant metapath is **minimal**, no need to test **supersets**.
- Testing if a metapath is dominant is **polynomial**.

# Using Pascal's triangle

- Build iteratively from the top.
- Only add set if not dominant.
- This guarantees we test only when necessary.



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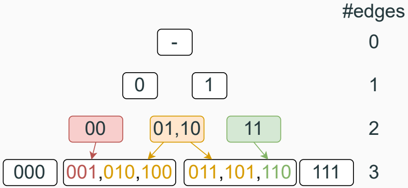
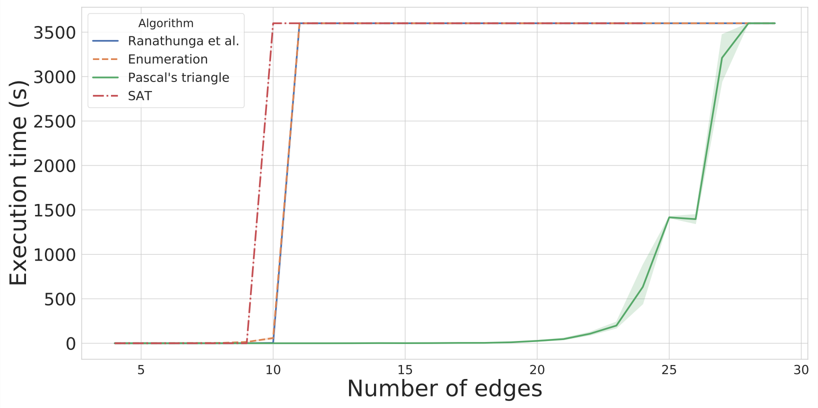


# Performance results




- SAT almost instant for generated instances.
- Pascal's triangle method up to 28 edges.

## Conclusion: 3rd axis

- Finding redundancies is NP-Hard.
- Roadblocks in SAT formulation.
- Efficient algorithm using Pascal's triangle.

## Conclusion

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- Microservices to enable leak-free multi-party workflows.
- Metagraphs are a useful model for policies.
- Policy verification to check implementations.
- Policy analysis to check specifications.

# Contributions of this thesis

This thesis therefore focuses on the prevention of data exposures, in workflows in particular.

| # | Contribution | Tool | Repository (`github.com/`) |
|---|---|---|---|
| 1 | Secure infrastructure design [6, 5] | Proof of Concept | `loicmiller/secure-workflow` |
| 2 | Policy verification [7, 5] | Policy verification | `loicmiller/policy-verification` |
| | | MGToolkit for Python 3 | `loicmiller/mgtoolkit` |
| 3 | Policy redundancy elimination [8] | Redundancy elimination | `loicmiller/policy-analysis` |
| | | SAT formulation | `loicmiller/fhep-sat-formulation` |

All code, data, results and figures are publicly available.


- Miller et al. "Towards Secure and Leak-Free Workflows Using Microservice Isolation". In: HPSR (2021).
- Miller et al. "Verification of Cloud Security Policies". In: HPSR (2021).
- Miller et al. "Securing Workflows Using Microservices and Metagraphs". In: Electronics (2021).
- Gil Pons et al. "Finding (s,d)-Hypernetworks in F-Hypergraphs is NP-Hard". In: arXiv (2022).

# Future Works

# Short term goals

- Improved SAT generation (De Morgan's Law).
- Explore related complexity issues.

## Midterm goals

- Explore security properties (separation of duties).
- Explore impact of workflow patterns (cancellation).

# Long term goals

- Constitution of a policy benchmark dataset.
- Distributed policy (least privilege).

## Distributed policy

- Split a single policy across distributed elements?
- Verify correctness? Least privilege?

- Policy composition (algebras).
- Who specifies what? Multiple languages?

**Thank you!**

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# Effect of policy engine on pod startup time

- Independent-samples t-test
- Two deployments: one with policy engine and one without.
- 130 observations per pod ($N = 1820$).

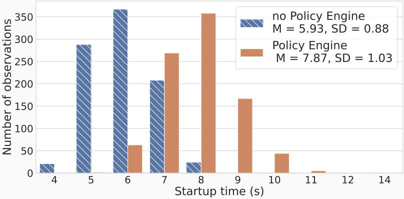
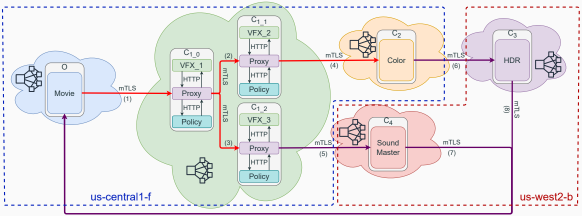



**Figure 2:** Startup time distribution

- $t(1818) = 43.19$, $p < 0.001$
- High effect size: $d = 1.985$
- High statistical power: $1 - \beta = 0.999$

Time increased by **2 seconds on average (32.72%)**.

# Effect of policy size on request duration




We analyze **intra-region** and **inter-region** communications.

One-way between subjects ANOVA.

40 observations per communication per scenario ($N = 1600$).

Policy scenarios: `no opa`, `all allow`, `minimal` ,+100 (+147%), +1000 (+1470%).

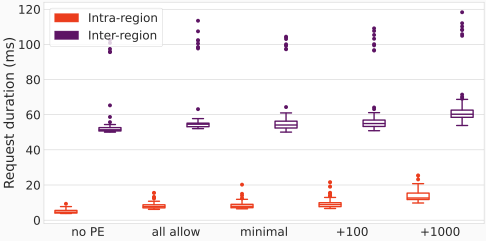
# High (low) impact on intra (inter) region request time

## Intra-region

- $F(4, 795) = 364.05$, $p < 0.001$
- **High** effect size: $\eta_p^2 = 0.65$

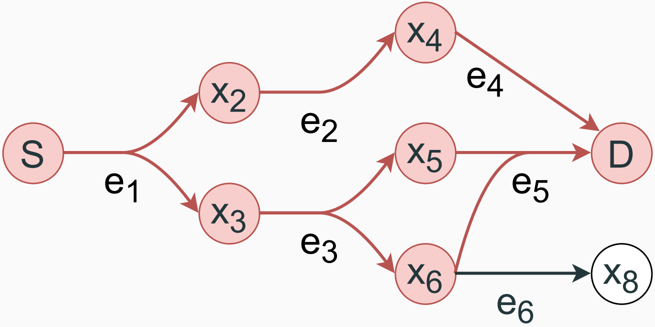
## Inter-region

- $F(4, 795) = 15.23$, $p < 0.001$
- **Low** effect size: $\eta_p^2 = 0.07$




- **Significant difference in request duration between the five scenarios for both types.**

# $(\mathcal{S},\mathcal{D})$-hypernetwork: Sum of all hyperpaths



# Finding (s,d)-Hypernetworks in F-Hypergraphs is NP-Hard

- FHEP reducible to SDHP.
- If FHEP is NP-complete, SDHP is NP-Hard.
- Reduction from 3-SAT (NP-Complete).

# We take an instance of 3-SAT

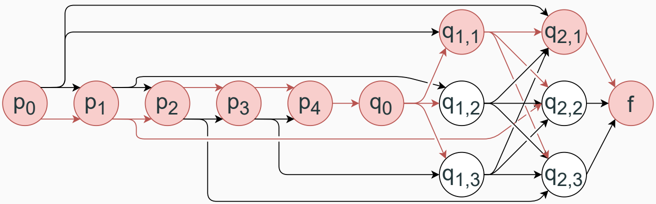
$$(v_1 \lor v_2 \lor \neg v_4) \land (v_1 \lor \neg v_2 \lor \neg v_3)$$

We construct a corresponding acyclic F-hypergraph.

Any forced edge hyperpath corresponds to a solution to 3-SAT instance.

# The construction

$$(v_1 \vee v_2 \vee \neg v_4) \wedge (v_1 \vee \neg v_2 \vee \neg v_3)$$




$p_0$ is the source. $f$ the destination.

$p_i$ for each variable. $q_{i,1}, q_{i,2}, q_{i,3}$ for each clause.

Edge where a variable appears in a clause.

# Complexity summary for finding a hyperpath

| | | | Edge-dom | Input-dom | Dom |
|---|---|---|---|---|---|
| Regular | Cyclic | B | P (linear) | P (linear) | P |
| | | F | P | P | P |
| | | BF | P | P | P |
| | Acyclic | B | P (linear) | P | P |
| | | F | P | P | P |
| | | BF | P | P | P |
| Forced Edge | Cyclic | B | NP-Hard [13] | ? | NP-Hard [13] |
| | | F | NP-Hard [13] | ? | NP-Hard [13] |
| | | BF | NP-Hard [13] | ? | NP-Hard [13] |
| | Acyclic | B | P (linear) [13] | ? | ? |
| | | F | ? | ? | ? |
| | | BF | ? | ? | ? |

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| | | F | P | P | P |
| | | BF | P | P | P |
| Forced Edge | Cyclic | B | NP-Hard [13] | ? | NP-Hard [13] |
| | | F | NP-Hard [13] | ? | NP-Hard [13] |
| | | BF | NP-Hard [13] | ? | NP-Hard [13] |
| | Acyclic | B | P (linear) [13] | ? | ? |
| | | F | NP-Hard [8] | ? | NP-Hard [8] |
| | | BF | NP-Hard [8] | ? | NP-Hard [8] |