Control-based runtime management of HPC systems with support for reproducible experiments

PhD Thesis Defense

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Ctrl-A and DataMove teams

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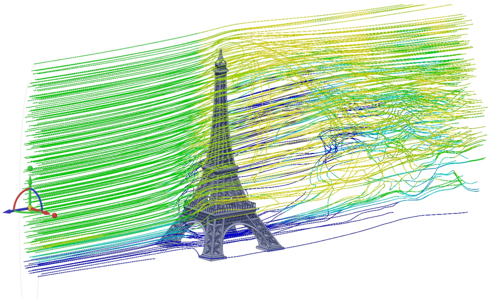


Computations too demanding $\rightsquigarrow$ need **several powerful** machines
$\hookrightarrow$ expensive $\rightsquigarrow$ shared $\rightsquigarrow$ **reservation process**

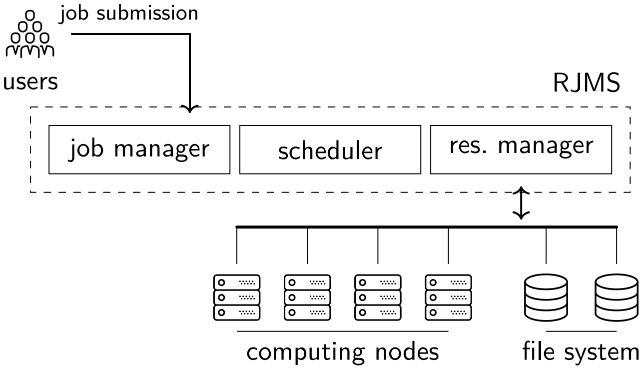
Resouces and Job Management System

HPC Jobs

- Some computations
- Static resource allocation
- Static time allocation

HPC Cluster

- Computing nodes
- Interconnected
- High speed network, I/O



Resources and **J**obs **M**anagement **S**ystem [Ble17]

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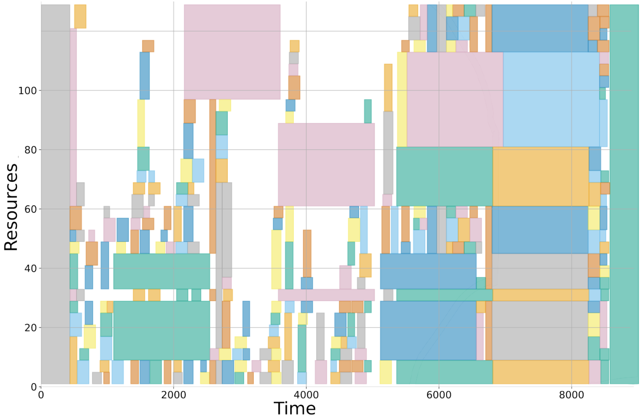

Gantt Chart

Idle Resources = Wasted Computing Power and Money

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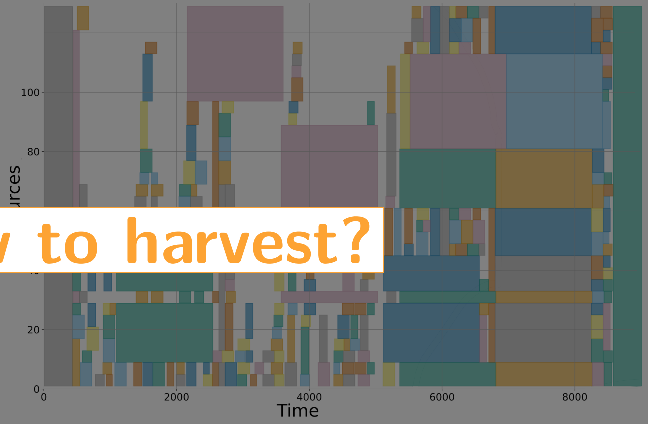


Gantt Chart

$\hookrightarrow$ **How to harvest?**

Idle Resources = Wasted Computing Power and Money

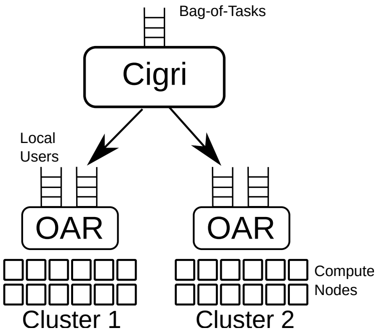
Harvesting Idle Resources

Main idea: Use smaller, killable jobs (e.g., Big Data [Mer+17], FaaS [Prz+22])

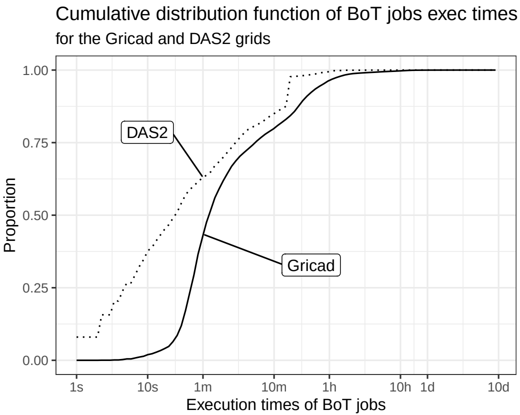
CiGri [GRC07]

- Grid middleware used at Gricad
- **Bag-of-tasks**: many, multi-parametric
- **Best-effort Jobs**: Lowest priority
- **Objectives**:
  - Collect grid idle resources
  - Reduce pressure on RJMS
- Submits like a *periodic tap*
  - submits jobs then,
  - waits for *all* jobs to terminate

  ↪ **suboptimal**!



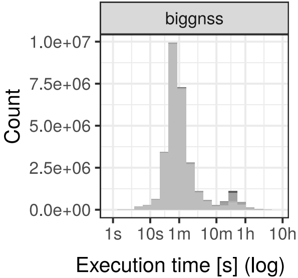
CiGri jobs [GRR22]



10 years, 44 Millions jobs

Example: BigGNSS [Dép+18]

- A lot of satellites $\Longrightarrow$ a lot of data
- Several stations $\rightsquigarrow$ **Campaigns**
- Subdivision of the processing $\rightsquigarrow$ **Jobs**
- Unique binary + different inputs



Problem

$\nearrow$ Harvesting $\Longrightarrow$ $\nearrow$ Performance Degradation $\rightsquigarrow$ **Trade-off**

$\hookrightarrow$ Unpredictability $\Longrightarrow$ **runtime management**

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In this PhD thesis

1. How to **submit** CiGri jobs to harvest idle resources with **controlled** degradation for priority users?

Problem

$\nearrow$ Harvesting $\implies$ $\nearrow$ Performance Degradation $\rightsquigarrow$ **Trade-off**

$\hookrightarrow$ Unpredictability $\implies$ **runtime management**

In this PhD thesis

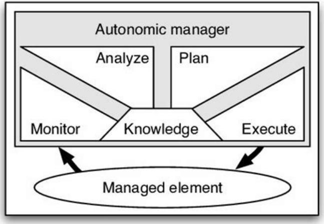
1. How to **submit** CiGri jobs to harvest idle resources with **controlled** degradation for priority users?
2. How to improve the **cost** and **reproducibility** of experiments on grid/cluster systems?

Harvesting idle resources

Runtime Management: Autonomic Computing (AC)

AC and the MAPE-K Loop [KC03]

- **Auto-regulation** given **high-level objectives**
- implementations: rules, AI, etc.



Runtime Management: Autonomic Computing (AC) and Control Theory

AC and the MAPE-K Loop [KC03]

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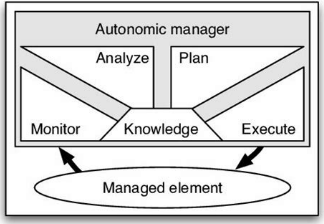
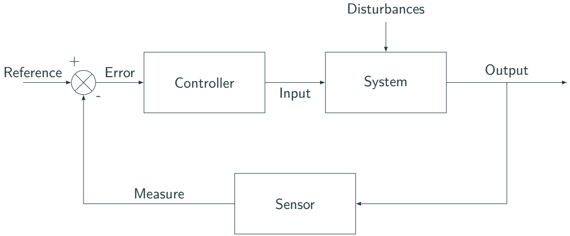


Control Theory

- Regulate dynamical systems
- physical systems
- mathematically proven properties
- performance, robustness, **explainability**

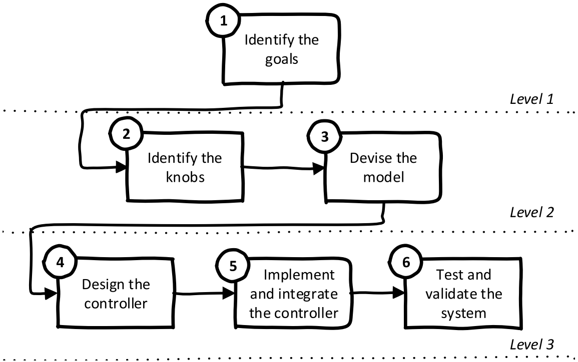


1. Identify the goals

Problem formulation

- Use Control Theory to....
- ...harvest idle resources...
- ...in a **non-intrusive** way
- max cluster utilization
- min degradation of performance

↪ Focus on I/O degradation



Steps to design a controller [Fil+15]

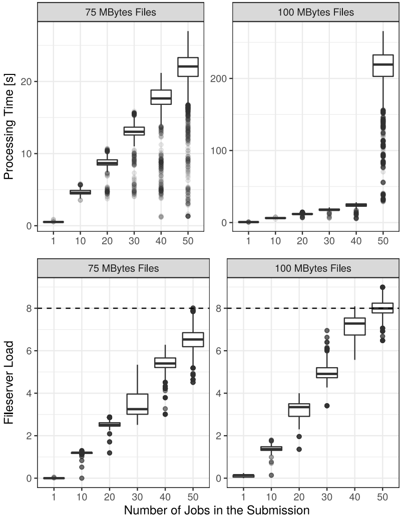
2. Identify the knobs

Actuators (u)

Number of jobs submitted by CiGri

Sensors (y)

- File-System (NFS):
  - **indirect** measure of overhead
  - `/proc/loadavg` [FZ87]
    - $\simeq$ number of processes running
    - well known by system administrators
    - Exponential Smoothing $\rightsquigarrow$ Inertia
      $\hookrightarrow$ Nice for the control



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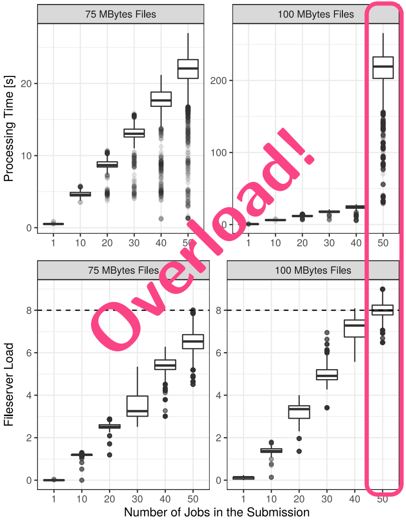

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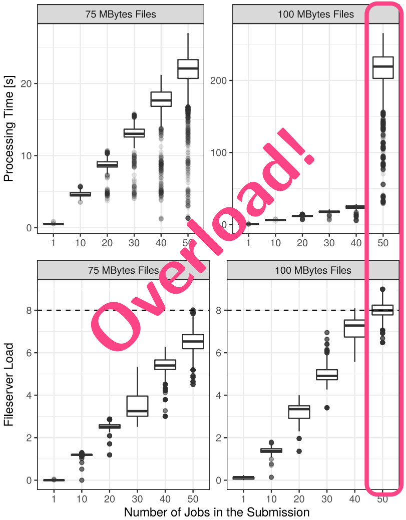
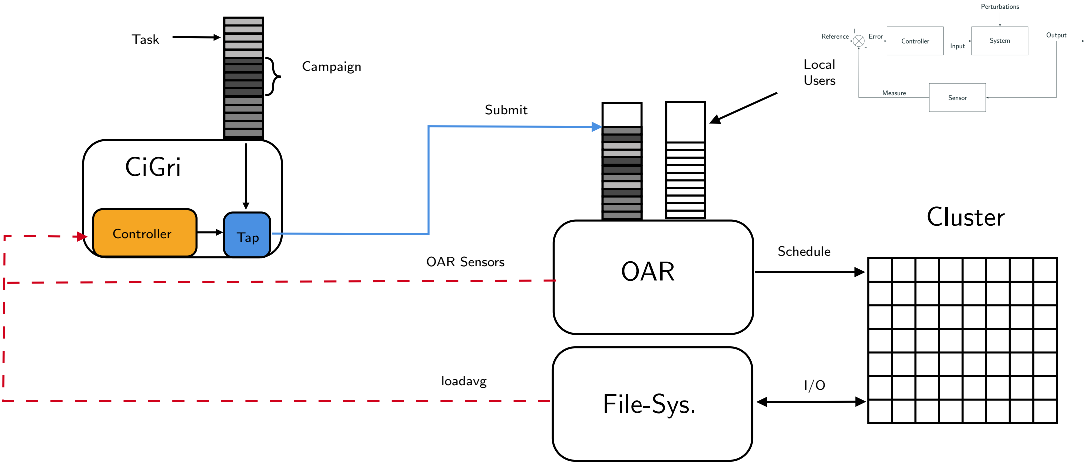
  - **know limits of sensor**
- Cluster: OAR API (nb running, waiting jobs)



Feedback loop in CiGri



Reference value: acceptable `load` on the File-System, chosen by system admins

3. Devise the model

First, a Model ... (i.e., how does the system behave without Control)

$$\mathbf{y}(k+1) = \sum_{i=0}^{k} a_i \times \mathbf{y}(k-i) + \sum_{j=0}^{k} b_j \times \mathbf{u}(k-j)$$

... then a (P) Controller (i.e., the Closed-Loop behavior)

$$\mathbf{u}(k) = \mathbf{K}_p \times Error(k)$$

Sensors & Actuators

- Actuator: #jobs to sub $\rightsquigarrow$ $\mathbf{u}$
- Sensor: FS Load $\rightsquigarrow$ $\mathbf{y}$
- $Error(k) = Reference - Sensor(k)$

Methodology

1. Open-Loop experiments (fixed $\mathbf{u}$)
2. Model parameters (a_i, b_j)
3. Choice controller behavior $(\mathbf{K}_*)$

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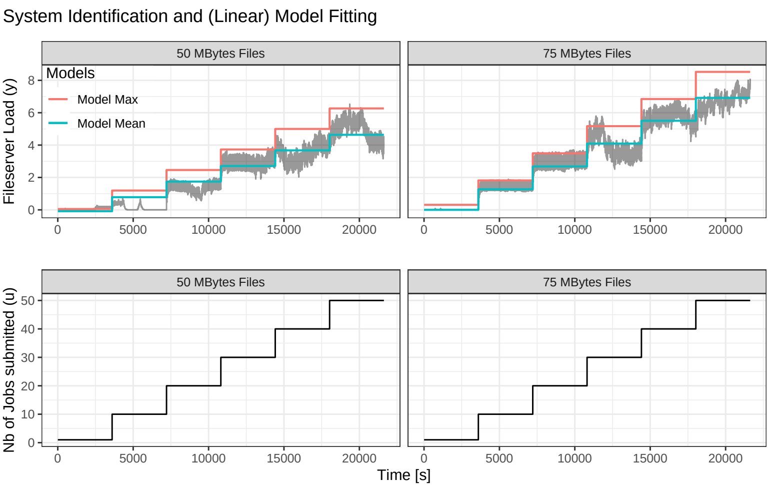
3. Devise the model - Open-Loop Experiments

- "step" inputs
- $\neq$ I/O loads (f)
- observe behavior
- **linear** model

$$y_{ss} = \alpha + \beta_1 f + \beta_2 u + \gamma f u$$



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In steady state (ss)

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$$\implies b \simeq (\beta_2 + \gamma f) \times (1-a)$$

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Where are we?

Open-Loop Experiments ✓

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Where are we?

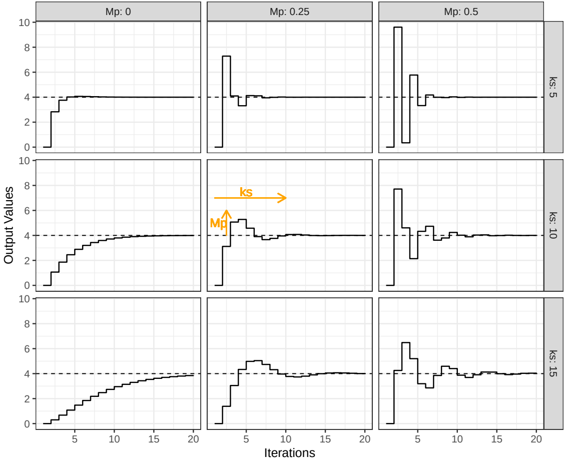
Open-Loop Experiments ✓ $\leadsto$ Model (1st order) $\mathbf{y}(k+1) = a \times \mathbf{y}(k) + b \times \mathbf{u}(k)$ ✓ $\leadsto$ Controller Gains $\mathbf{K}_p, \mathbf{K}_i, \mathbf{K}_d$

4. Design the controller

Controller Gains are ...
functions of the model and

- k_s: maximum **time** to steady state
- M_p: maximum **overshoot** allowed

Closed loop behaviour of our system for different values of (ks, Mp)



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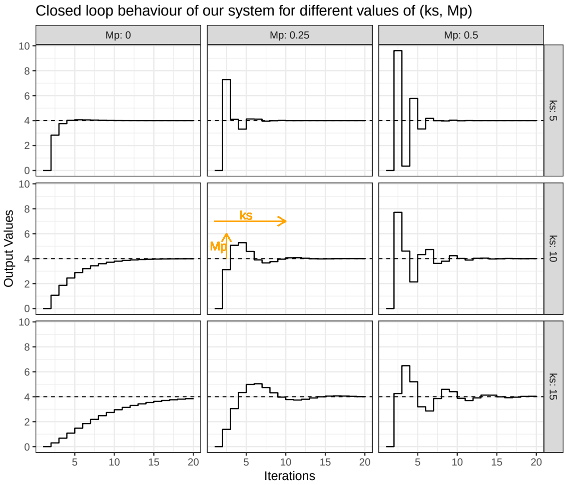

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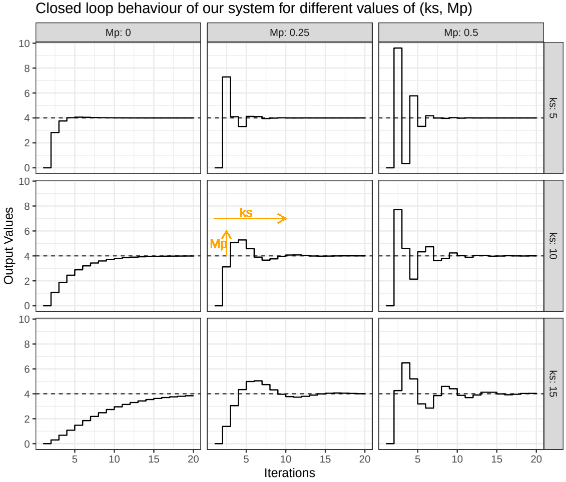
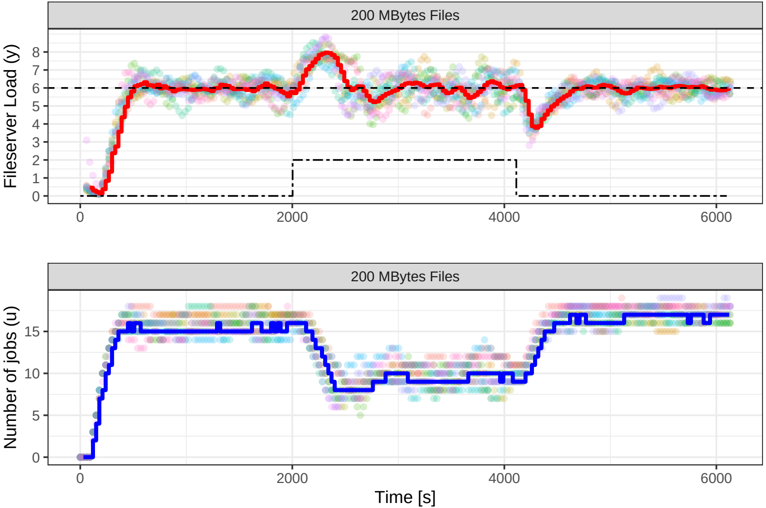
Non-Intrusive Harvesting

- no overshoot
- but "fast" response



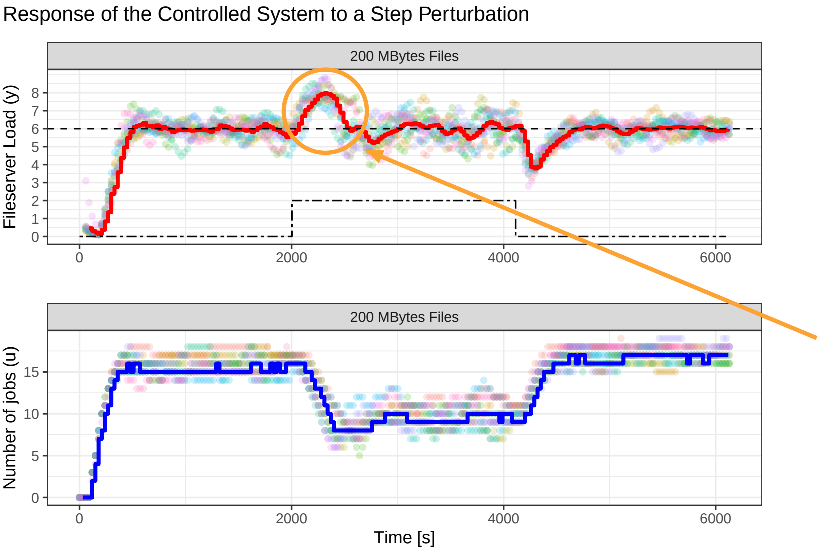
5./6. Implement and validate the controller - Evaluation with synthetic jobs

Response of the Controlled System to a Step Perturbation



- constant reference
- synthetic jobs
- step disturbance

Manage to control the load of the File-System



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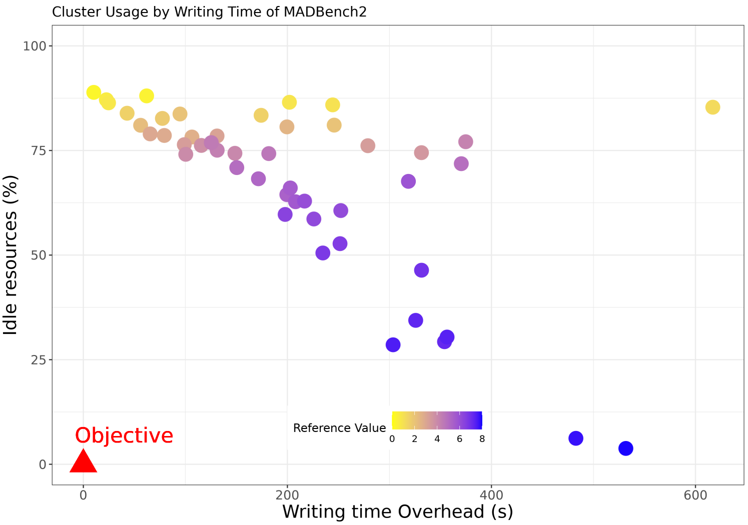
Manage to control the load of the File-System

takes time to react

↪ might cause **overload**

Trade-off: Idleness versus Performance degradation (I/O Overhead)



- MADBench2 [Bor+07]
- various reference values
- compute idle resources
- compute I/O overhead

Trade-off between Harvesting & I/O overhead through the reference value

A note on controllers' reusability

- Controllers **linked** to the identified system
- what if new cluster? new configuration?
- Grid/Cluster administrators
  ↪ **not** control theory experts!
- compared 3 controllers (w.r.t. portability, guarantees, competence required)
- example: Portability vs. Performance

↪ **gave recommendations** for system administrators

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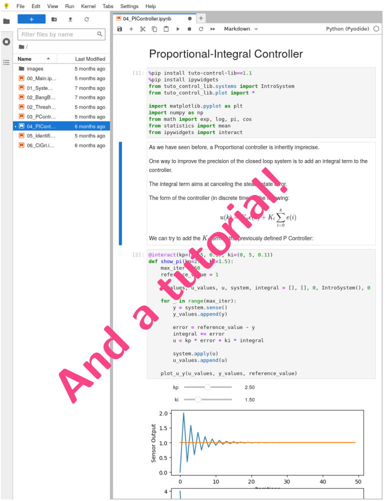

Control-based harvesting of idle resources: Wrapping up

Objectives

- Control CiGri submissions based on File-System load ✓
- Control CiGri submissions to reduce idle/killed wasted time ✓
- Can merge controllers! (with some subtelties)
- Guidelines for system administrators ✓
- Tutorial to introduce control theory to computer scientists ✓

Limitations and Perspectives

- Tested with *synthetic* jobs $\rightsquigarrow$ real trace
- Need more info about CiGri jobs' I/O patterns
- Submissions to several clusters
- Sensor for Parallel File-System (PFS) ?

Objectives

- Control CiGri submissions based on File-System load ✓
- Control CiGri submissions to reduce idle/killed wasted time ✓
- Can merge controllers! (with some subtelties)
- Guidelines for system administrators ✓

Take Away: Control Theory **valuable approach** to exploit such trade-offs

- Tutorial to introduce control theory to computer scientists ✓

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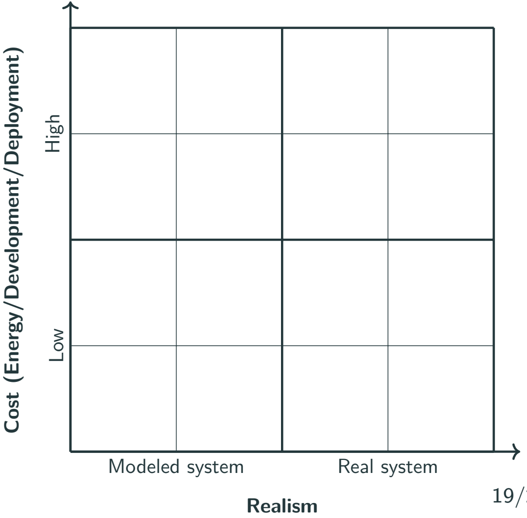
Experiment costs and reproducibility

A grid middleware needs . . . a grid!

How many machines required to perform **realistic** experiments on a grid middleware like CiGri?



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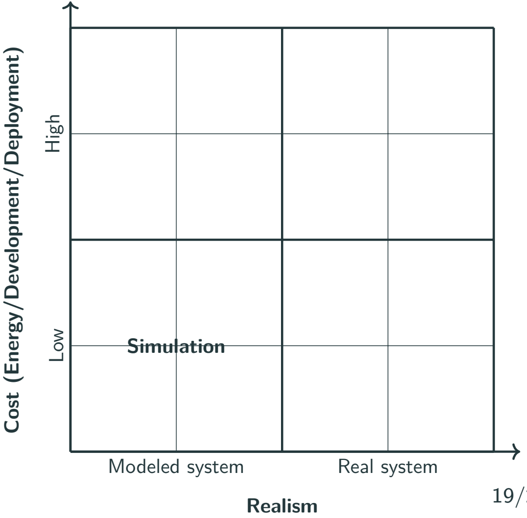

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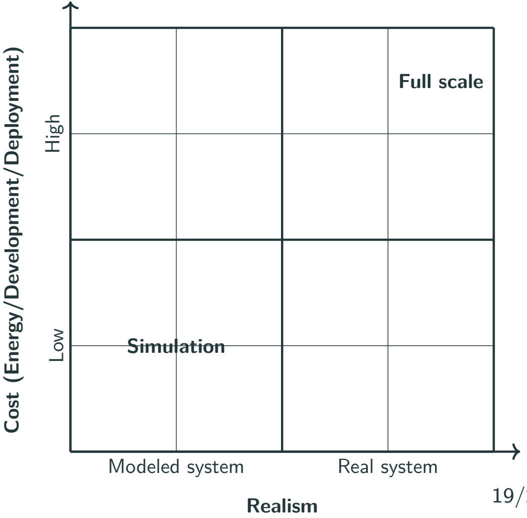

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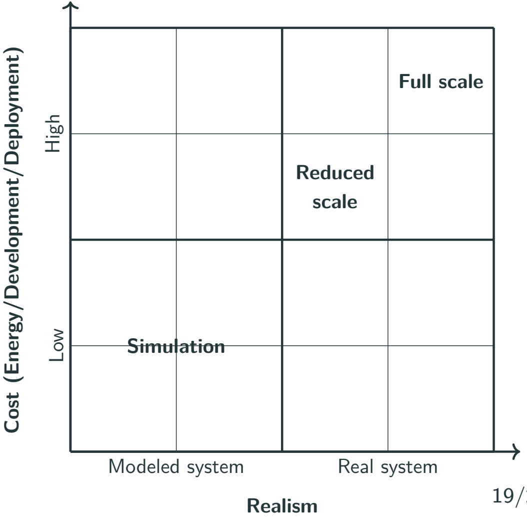
- **Simulation**: fast ☺, modeled ☹, poor sensor support ☹, poor PFS support ☹
- **Full scale**: real environment ☺, expensive and difficult ☹
- **Reduced scale**: real environment ☺, cheaper ☺, **realistic ?** ☹

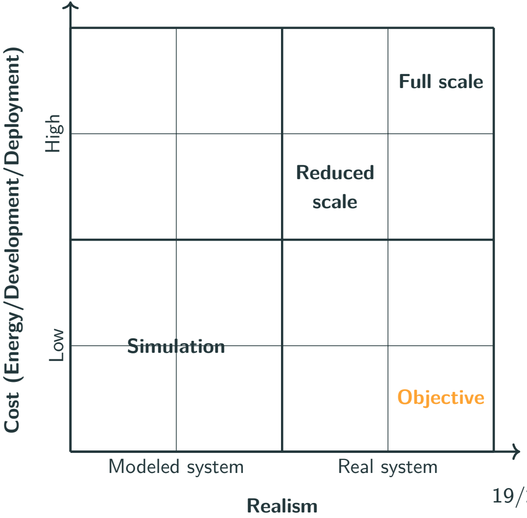


A grid middleware needs . . . a grid!

How many machines required to perform **realistic** experiments on a grid middleware like CiGri?

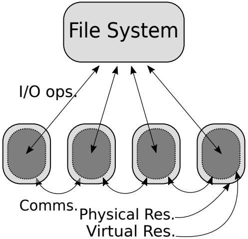
- **Simulation**: fast ☺, modeled ☹, poor sensor support ☹, poor PFS support ☹
- **Full scale**: real environment ☺, expensive and difficult ☹
- **Reduced scale**: real environment ☺, cheaper ☺, **realistic ?** ☹

Objective: Low cost, realist experiments on the real system



Emulating a full scale cluster by folding its deployment [Gui+23]

The idea: Deploy more "virtual" resources on one physical machine (≃ oversubscribing)



Scale 1:1

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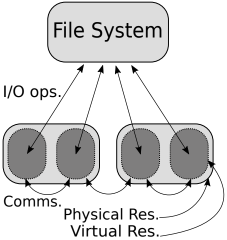

Scale 1:2

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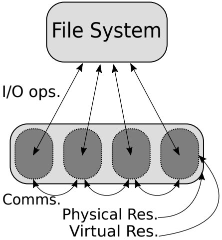

Scale 1:4

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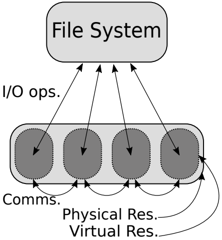

Scale 1:4

+ less resources deployed
+ represents full scale system
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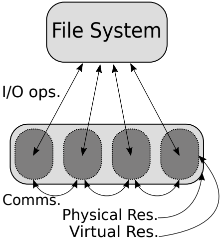

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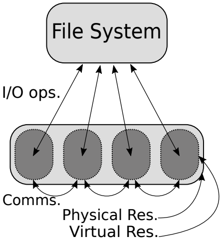

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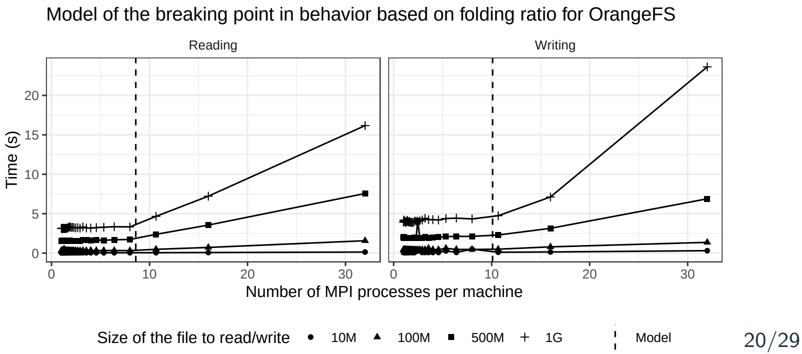

Protocole:

- IOR [Cal23]
- increase folding
- NFS, OrangeFS

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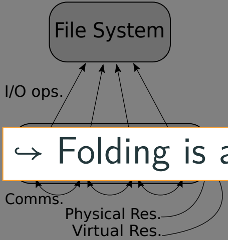

Scale 1:4

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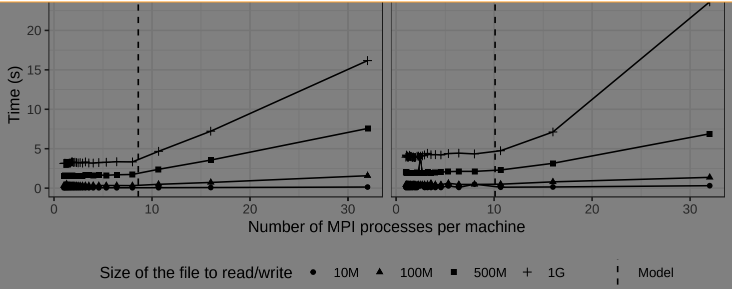
↪ Folding is appropriate until a **breaking point** that we can model



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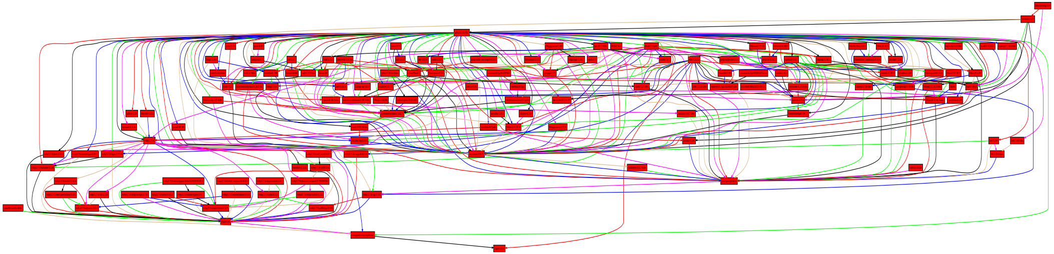
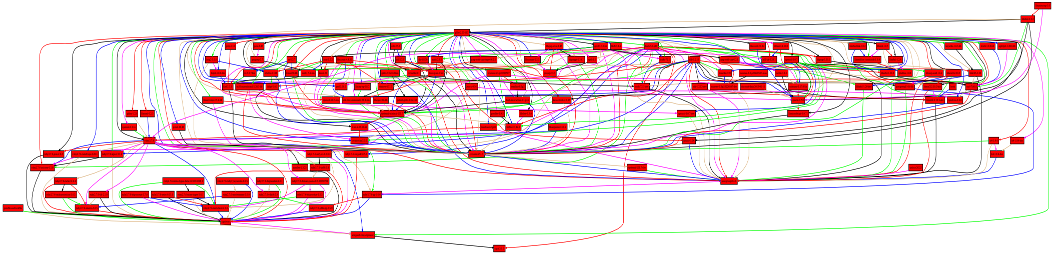
Complex Software Environments



Graph of CiGri's software dependencies

Complex Software Environments



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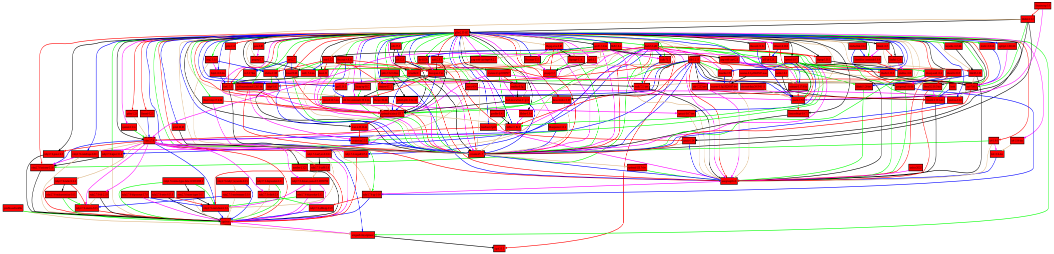

Graph of CiGri's software dependencies

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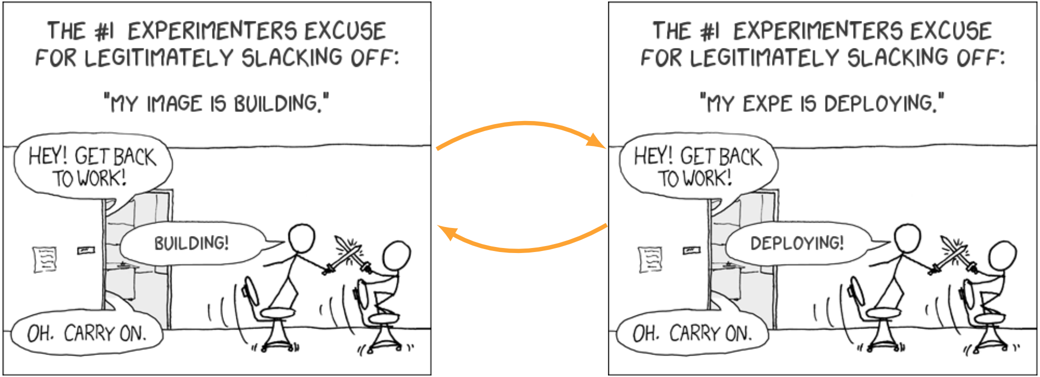
How to **develop/deploy easily** complex software environments in a **reproducible** fashion?

Generating Distributed Software Environments

↪ **Difficult**, **Time-consuming**, **Script-based** tools, and **Iterative** process



$\simeq$ **10/15 mins** $\qquad$ $\simeq$ **5/10 mins**

↪ Easy to **depend on an external state**: base image, apt mirror, `git` repository

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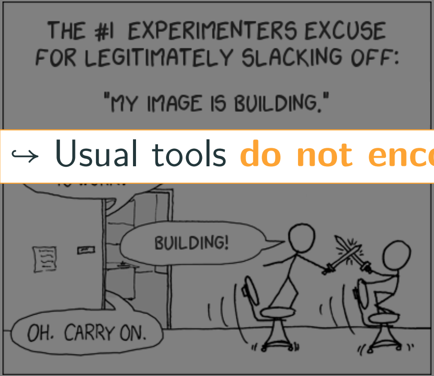

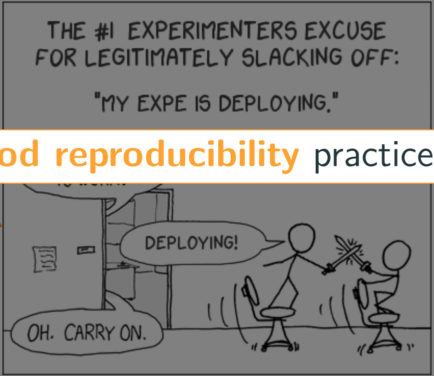

↪ Usual tools **do not encourage good reproducibility** practices

$\simeq$ **10/15 mins**

$\simeq$ **5/10 mins**

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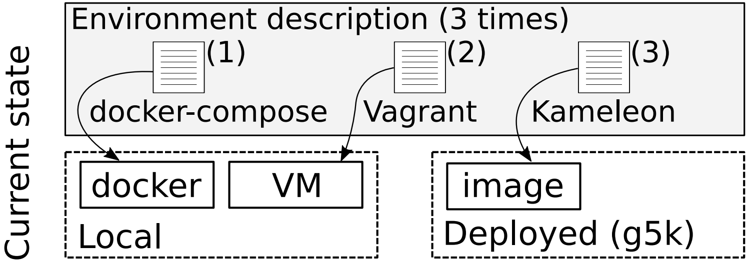
One tool, One platform



'So essentially, I want to create a debian12-nfs.qcow2 for VMs equivalent to grid5000's debian12-nfs image. One ***painful way*** *to achieve this would be to install every single thing using the package manager and resolving conflicts by hand.'* *(Grid'5000 User, 2023)*

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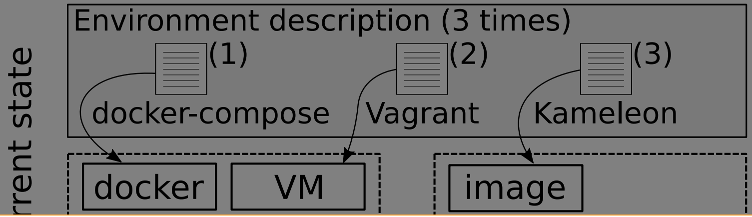
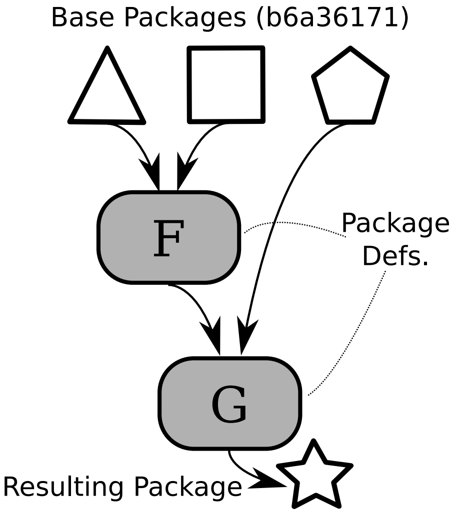


↪ Be able to **develop** distributed environments **locally** and then export

'So essentially, I want to create a debian12-nfs.qcow2 for VMs equivalent to grid5000's debian12-nfs image. One ***painful way*** *to achieve this would be to install every single thing using the package manager and resolving conflicts by hand.'* *(Grid'5000 User, 2023)*

Functional package managers

- Nix, Guix **reproducible by design!**
- packages = functions
  - inputs = dependencies
  - body = commands to build the package
- base packages defined in Git
- sandbox, no side effect
- `/nix/store/`*hash(inputs)*`-my-pkg`
- immutable, read-only
- **precise** definition of `$PATH`
- **can build: container, VM, *system images***



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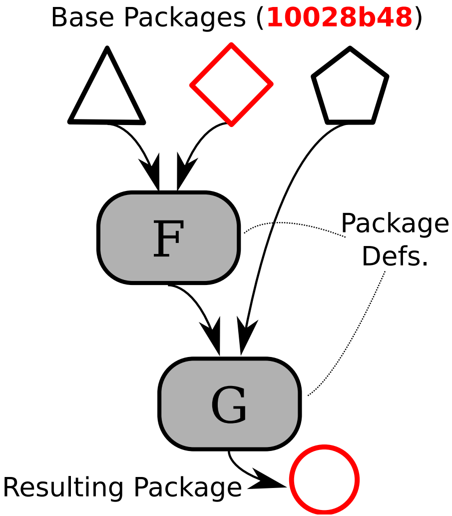


NixOS Compose [Gui+22]

```
{ pkgs, ... }:
let k3sToken = "..."; in {
  roles = {
    server = { pkgs, ... }: {
      environment.systemPackages = with pkgs; [
        k3s gzip
      ];
      networking.firewall.allowedTCPPorts = [
        6443
      ];
      services.k3s = {
        enable = true;
        role = "server";
        package = pkgs.k3s;
        extraFlags = "--agent-token ${k3sToken}";
      };
    };
    agent = { pkgs, ... }: {
      environment.systemPackages = with pkgs; [
        k3s gzip
      ];
      services.k3s = {
        enable = true;
        role = "agent";
        serverAddr = "https://server:6443";
        token = k3sToken;
      };
    };
  };
}
```

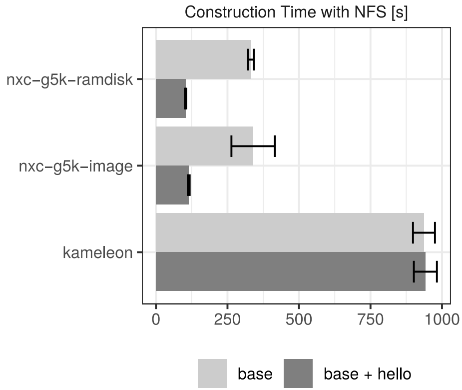
Packages

Ports

Services

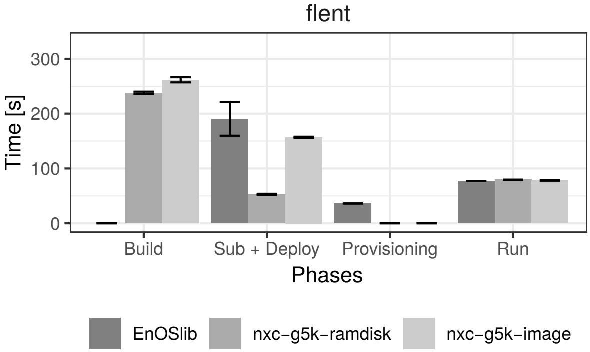
- Python + Nix ($\simeq$ 4000 l.o.c.)
- developing/deploying distributed systems
- **single description** (in Nix), multiple targets
- docker-compose, VM, ramdisk, system image
- can **quickly** setup distributed envs **locally!**
- build, deploy, connect: **unique interface**
- contextualization (ssh keys, `/etc/hosts`, etc.)
- integration with Execo [Imb+13]
- a few, but happy, users ☺

Kameleon [Rui+15]



build ⇝ modify (add `hello`) ⇝ build

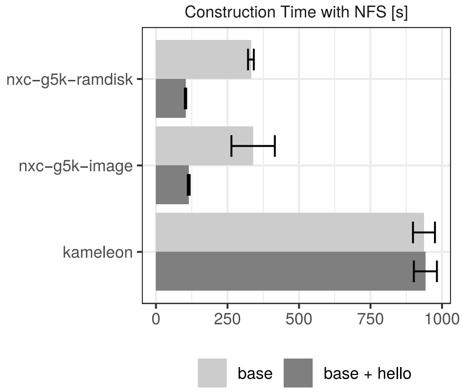
EnOSlib [Che+22]



NixOS Compose ⇝ provisioning done in image

Comparisons - Setting up a distributed environments on Grid'5000

Kameleon [Rui+15]



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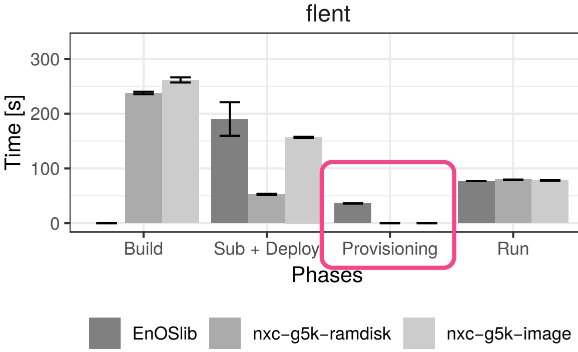

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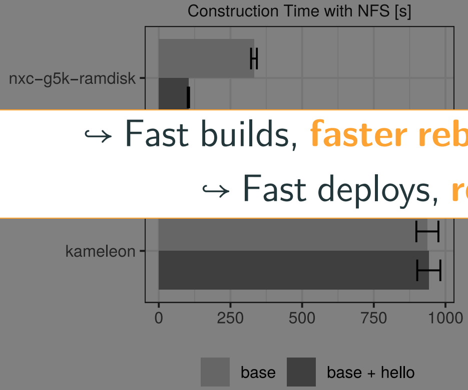

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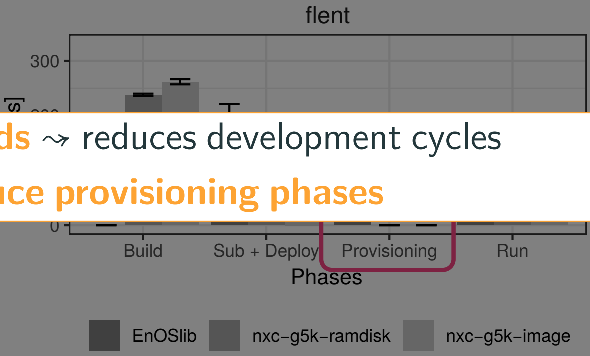


↪ Fast builds, **faster rebuilds** ⇝ reduces development cycles

↪ Fast deploys, **reduce provisioning phases**

NixOS Compose ⇝ provisioning done in image

build ⇝ modify (add `hello`) ⇝ build

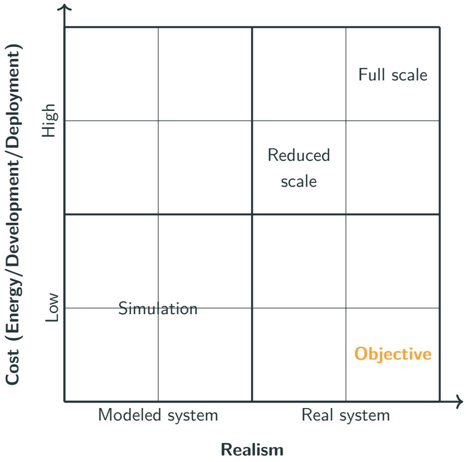
Experiment costs and reproducibility: Wrapping up

Objectives

- Reduce cost of experimenting with grid/cluster middlewares ✓
- Improve development cycles for reproducible experiments ✓

Limitations and Perspectives

- More popular Parallel File-Systems
- Source of the performance loss unclear
- Other platforms for NixOS Compose
- Hybrid/folded deployments
- Simulation: PFS and sensors



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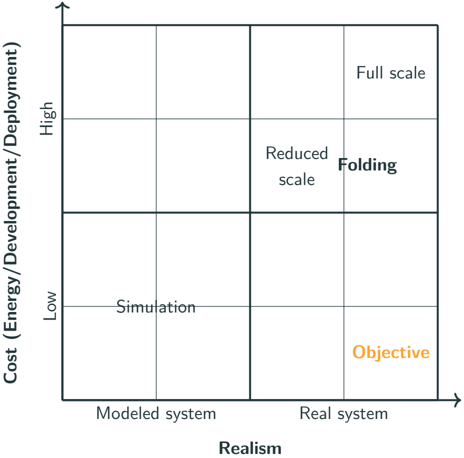

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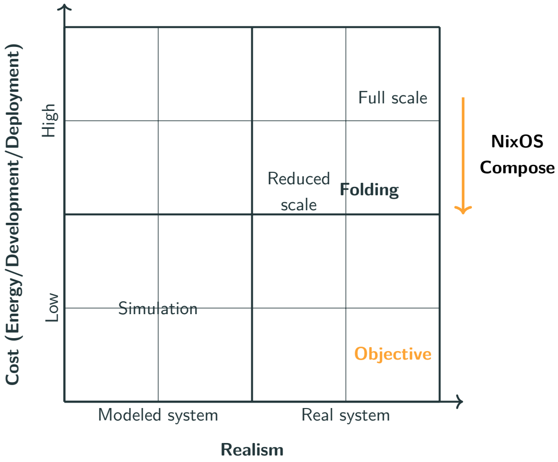

Experiment costs and reproducibility: Wrapping up

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Take Away: Reduced the time/energy cost to experiment with distributed systems, and improve reproducibility

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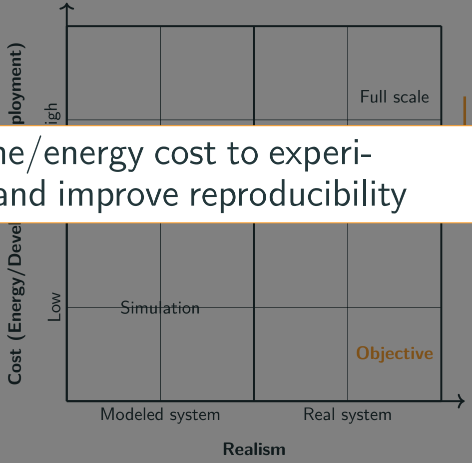

Concluding thoughts

Conclusion

Initial Problem

How to harvest HPC idle resources while controlling the impact on the priority jobs?

Contributions

- Design/implement an Autonomic loop in CiGri...
  - to control the load of the File-System $\rightsquigarrow$ control overhead, avoid overload
  - to reduce the wasted computing power (idle and killed)
- ... using Control Theory
  - yields guarantees and explainability
  - guidelines for system administrators, tutorial
- Reduce experiment costs
  - reduce number of machines to deploy without loss of realism
  - tool for developing and deploying reproducible distributed environments

Open question

CiGri
Improve usage of computing clusters

Folding
Reduce number of physical machines required to represent a full scale cluster

NixOS Compose
Reduce development time, and reduce "test" deployments

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But can it introduce a **rebound effect**?

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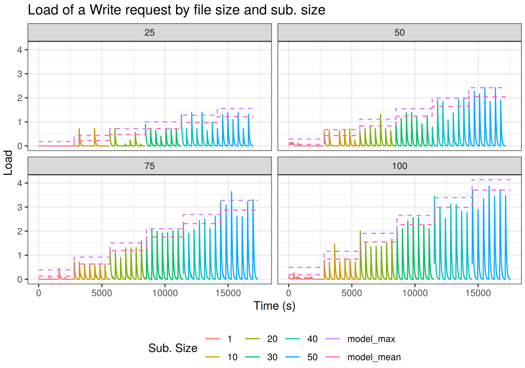
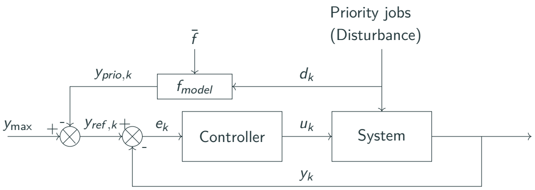
  - dynamic reference value
  - based on number of **priority jobs** and **historical I/O data** (e.g., Darshan [Car+11])





Beyond idle resources

Wasted computing power: Idle resources, but also

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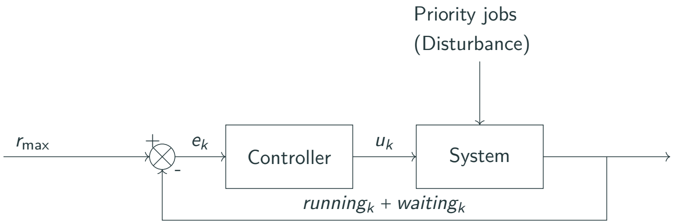

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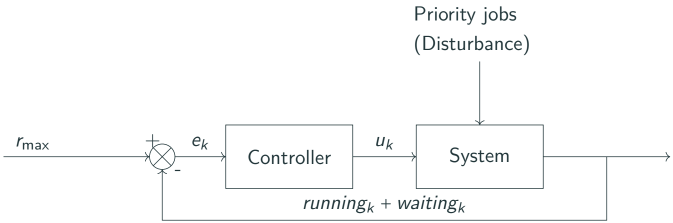

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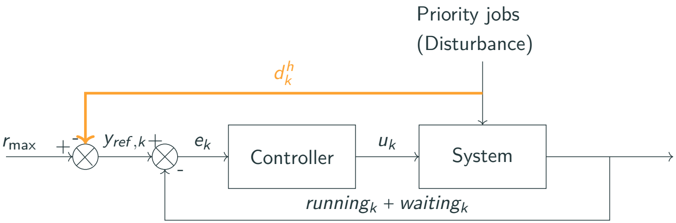

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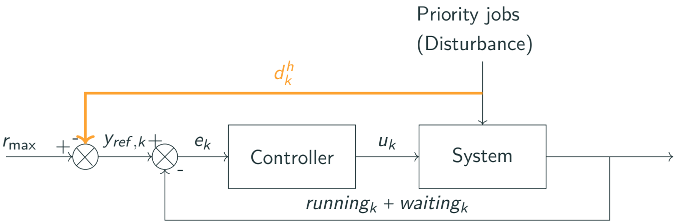

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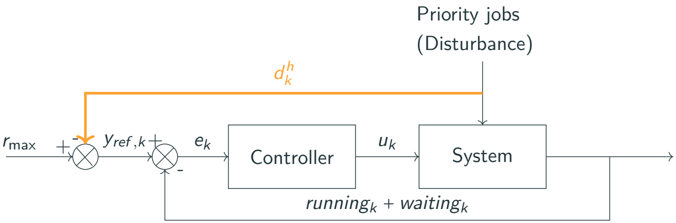

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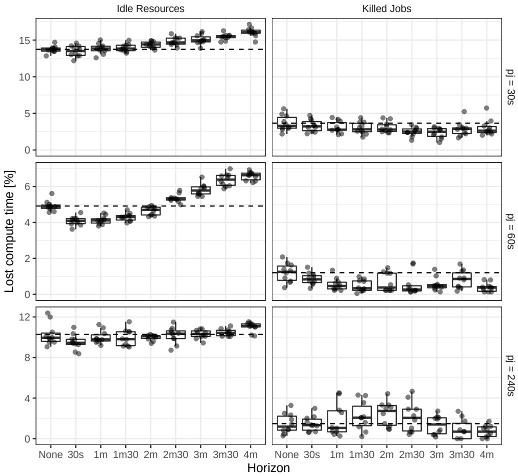
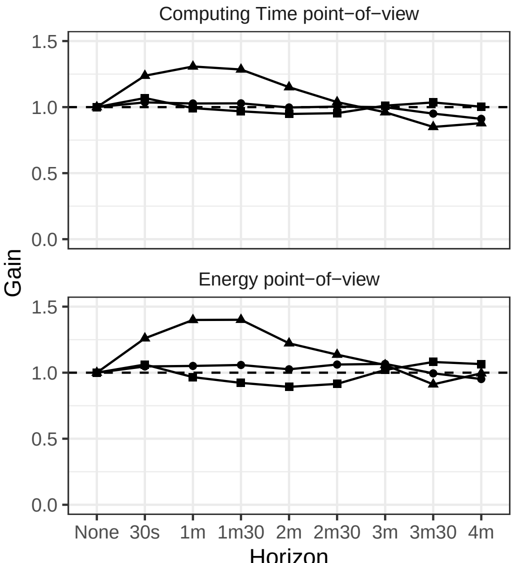
Can reduce **both idle and killed** time, and energy usage!

Beyond idle resources - Results





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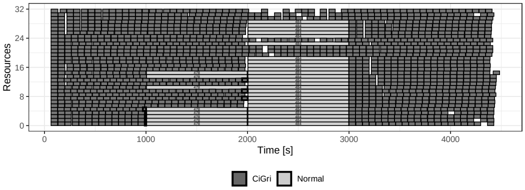
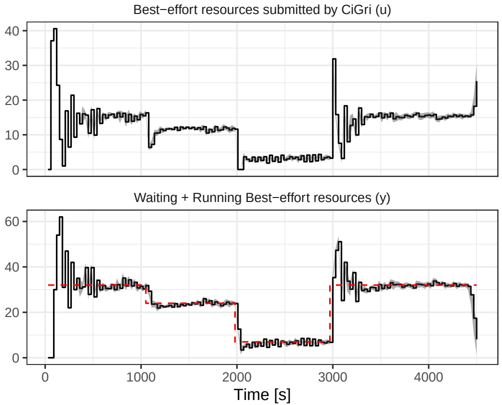
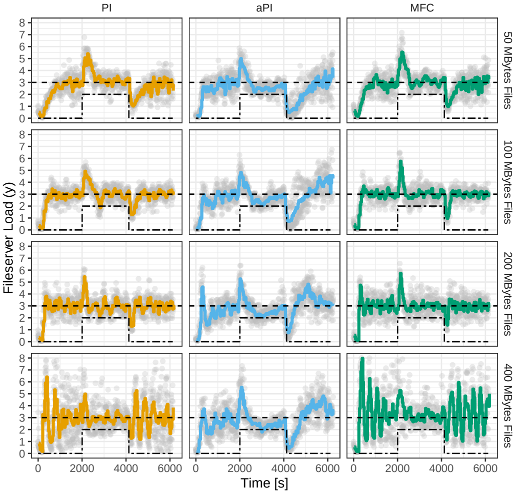


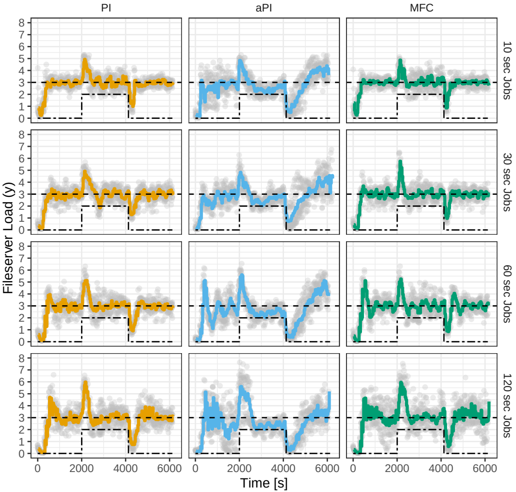


Reusability

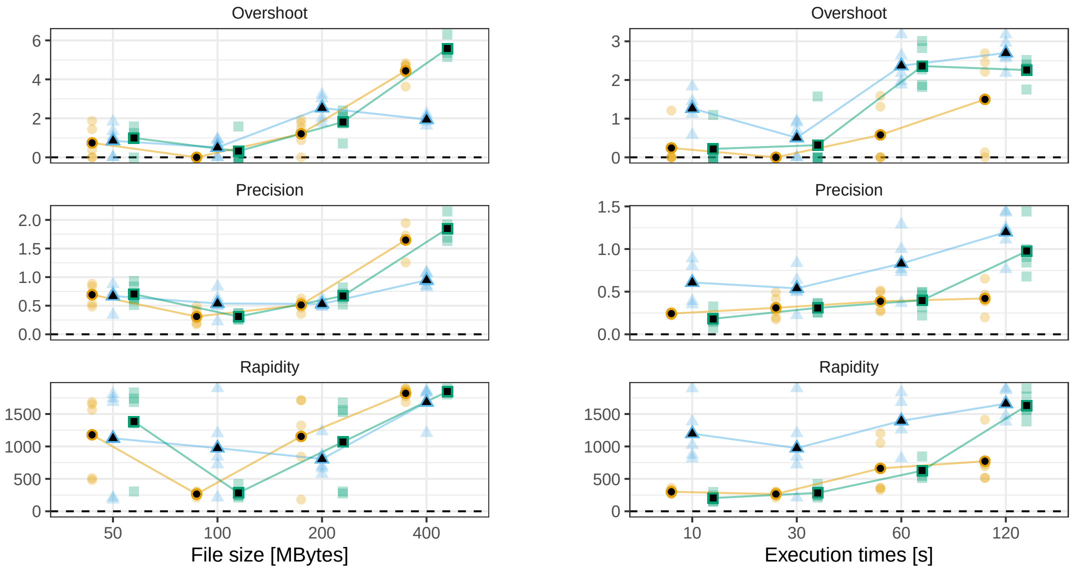
Comparison with variations in the I/O impact of jobs



Comparison with variations in the execution time of jobs



Reusability - Metrics



How to store the packages?

Usual approach: Merge them all

- Conflicts
- `PATH=/usr/bin`

```
/usr
├── bin
│   └── myprogram
└── lib
    ├── libc.so
    └── libmylib.so
```

Nix approach: Keep them separated

+ Pkg variation
+ Isolated
+ Well def. `PATH`
+ Read-only

```
/nix/store
├── y9zg6ryffgc5c9y67fcmfdkyyiivjzpj-glibc-2.27
│   └── lib
│       └── libc.so
└── nc5qbagm3wqfg2lv1gwj3r3bn88dpqr8-mypkg-0.1.0
    └── bin
        └── myprogram
    └── lib
        └── libmylib.so
```

References i

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