Improving the Scalability and Security of Execution Environments for Auto-Graders in the Context of MOOCs

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Programming Education with MOOCs

OPEN HPI

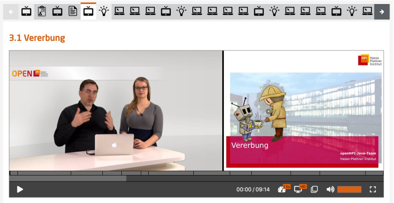
openSAP

mooc.house

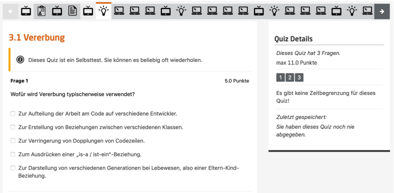
MOOCs

> **175.000 Enrollments**
> in Programming MOOCs

Videos



Quizzes



Programming Exercises

</> CodeOcean

(Staubitz et al. 2016)

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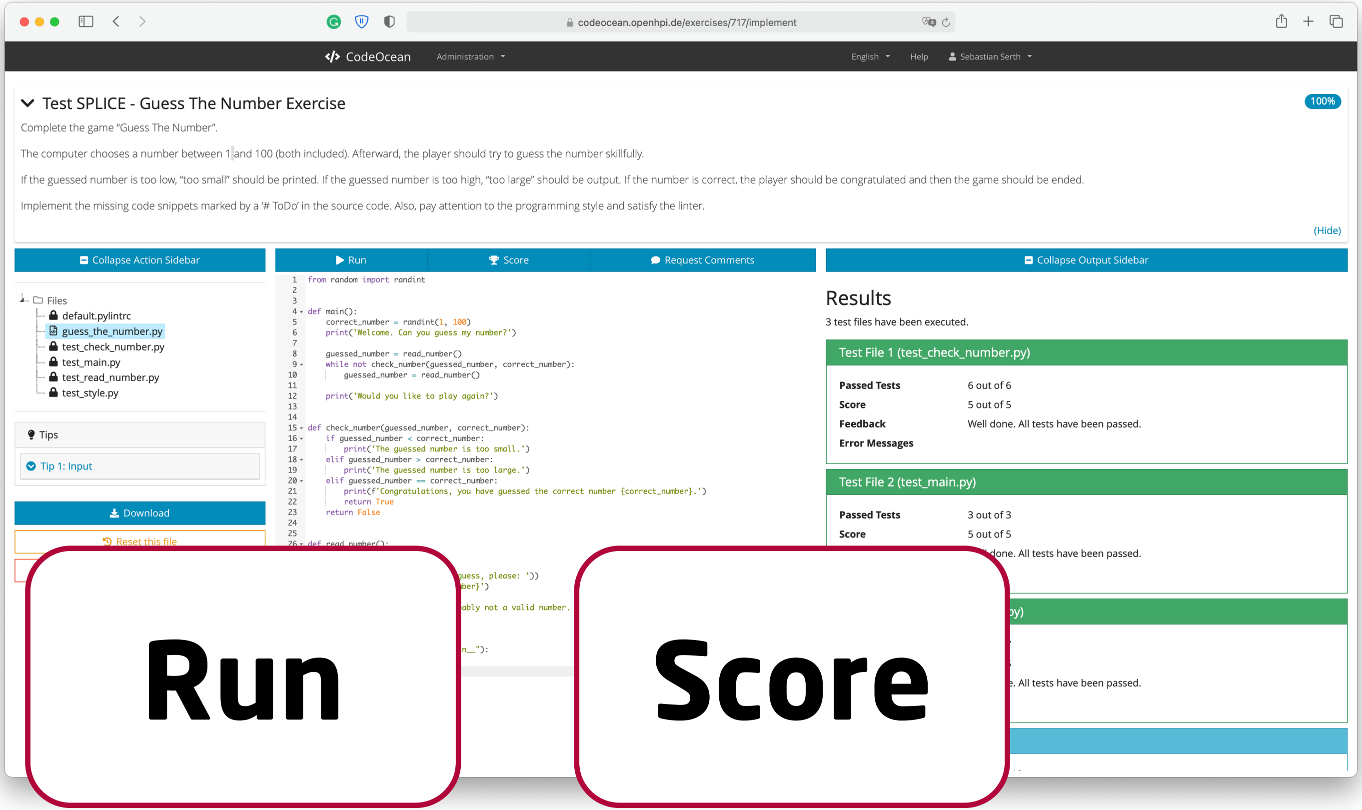
CodeOcean

Code Execution and Grading in the Browser



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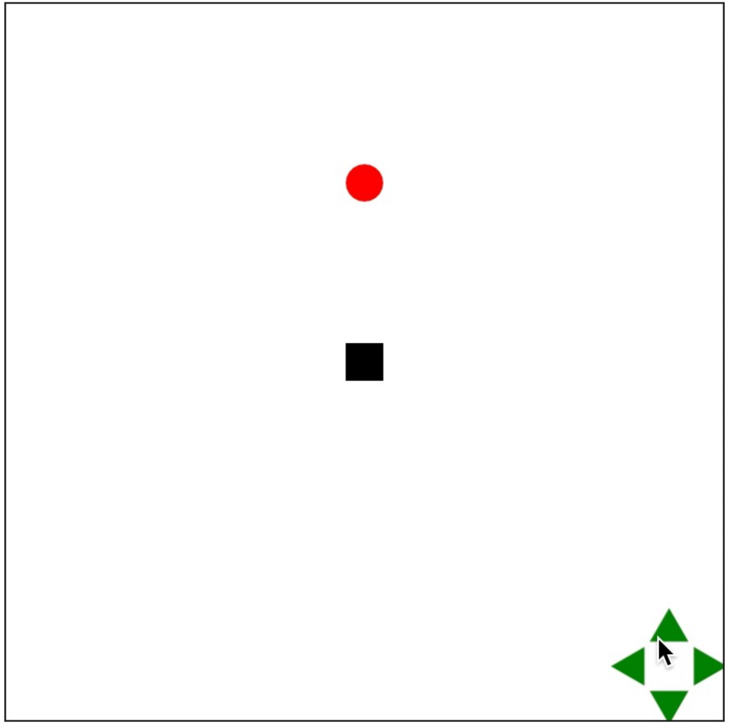
CodeOcean

Interactive Elements and Detailed Score Output



Your guess, please: | Send

`Welcome. Can you guess my number?`

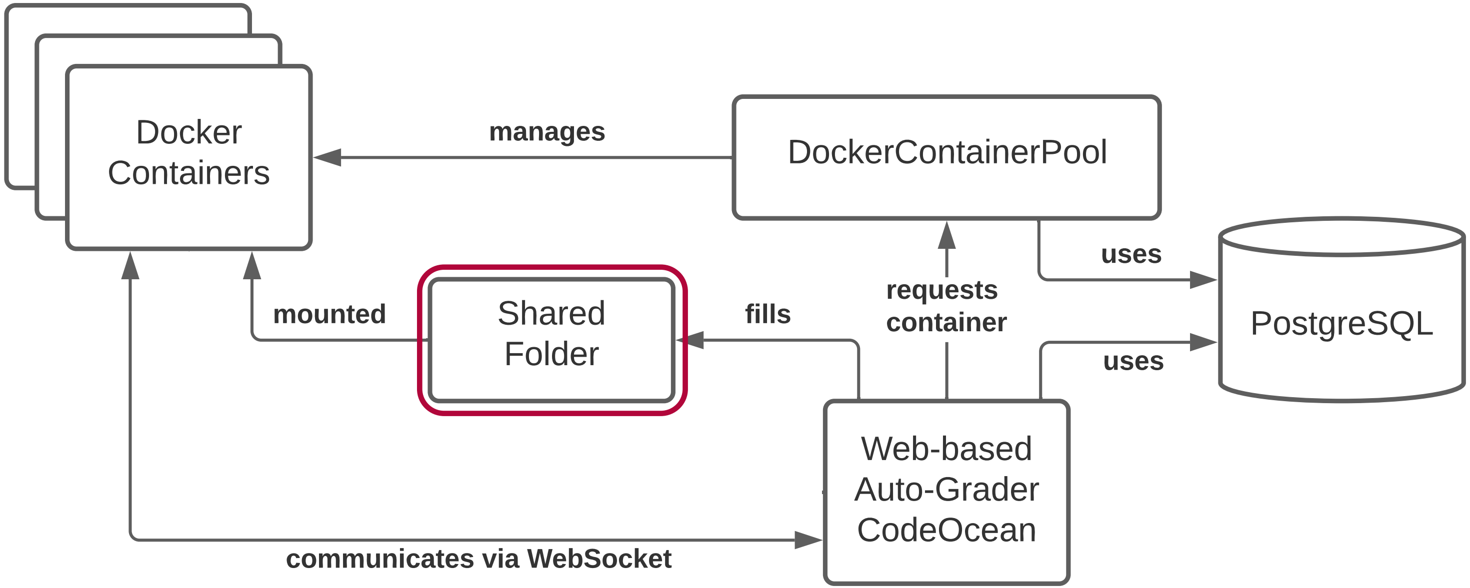
Linter Feedback (test_style.py)

Code Rating	4.64 out of 10
Score	0.46 out of 1
Feedback	Es gibt noch einige Hinweise vom Linter.

Messages

- convention:
  - superfluous-parens: Unnecessary parens after 'if' keyword (aufgabe314.py: 27)
  - wrong-import-position: Import "from turtle import *" should be placed at the top of the module (aufgabe314.py: 18)
  - multiple-statements: More than one statement on a single line (aufgabe314.py: 25, quadrat())
- error:
  - function-redefined: function already defined line 2 (aufgabe314.py: 5, dreieck())
- warning:
  - redefined-outer-name: Redefining name 'winkel' from outer scope (line 1) (aufgabe314.py: 6, dreieck())
  - redefined-builtin: Redefining built-in 'len' (aufgabe314.py: 14, dreieck())
  - unreachable: Unreachable code (aufgabe314.py: 17, dreieck())
  - unused-variable: Unused variable 'len' (aufgabe314.py: 14, dreieck())
  - pointless-string-statement: String statement has no effect (aufgabe314.py: 32)
- refactor:

CodeOcean
Current System Architecture



- **Architectural issues** with the shared folder:
  - Difficult horizontal scaling
  - Increased attack surface

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Requirements Analysis
Approach

- User-centered Design Thinking approach:
  (Meinel et al. 2016)
  1. Interviews with different stakeholder representatives
     a) Learners
     b) Teachers
     c) Administrators
  2. Derive personas to visualize user needs and their pain points
  3. Decide on a subset of features to address
  4. Evaluate technical solutions for these personas

- Analysis of past executions on CodeOcean since 2015

Related Work
Security Considerations

Assessing code submissions
(Garmann 2013)

Dynamic code analysis

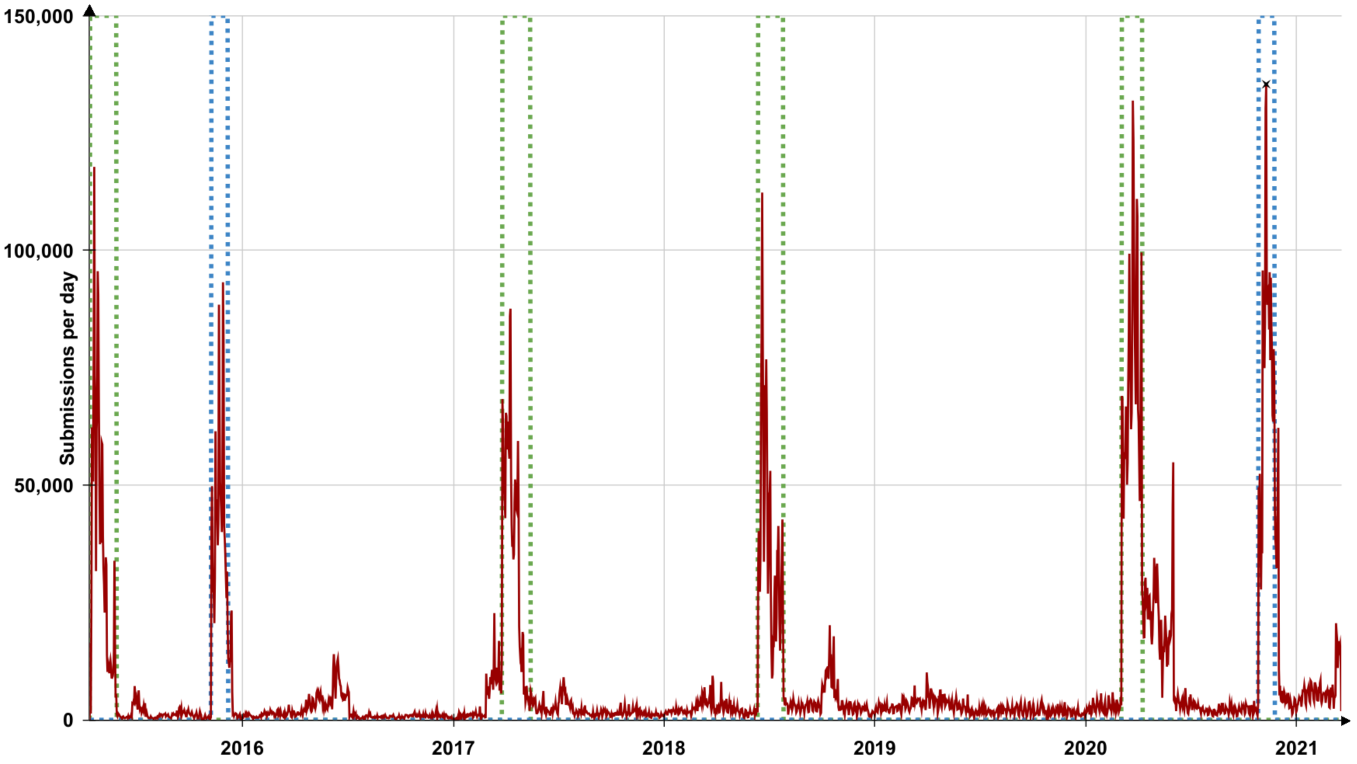
- Code under investigation is executed
  - Security implications
    - Language-specific
      using the Java Security Manager
      (Strickroth 2019)
    - Container-based
      using Docker
      (Breitner et al. 2016)

Static code analysis

- Code inspection without executing the code under investigation

→ Other scalability and security considerations

Requirements Analysis
Past Performance



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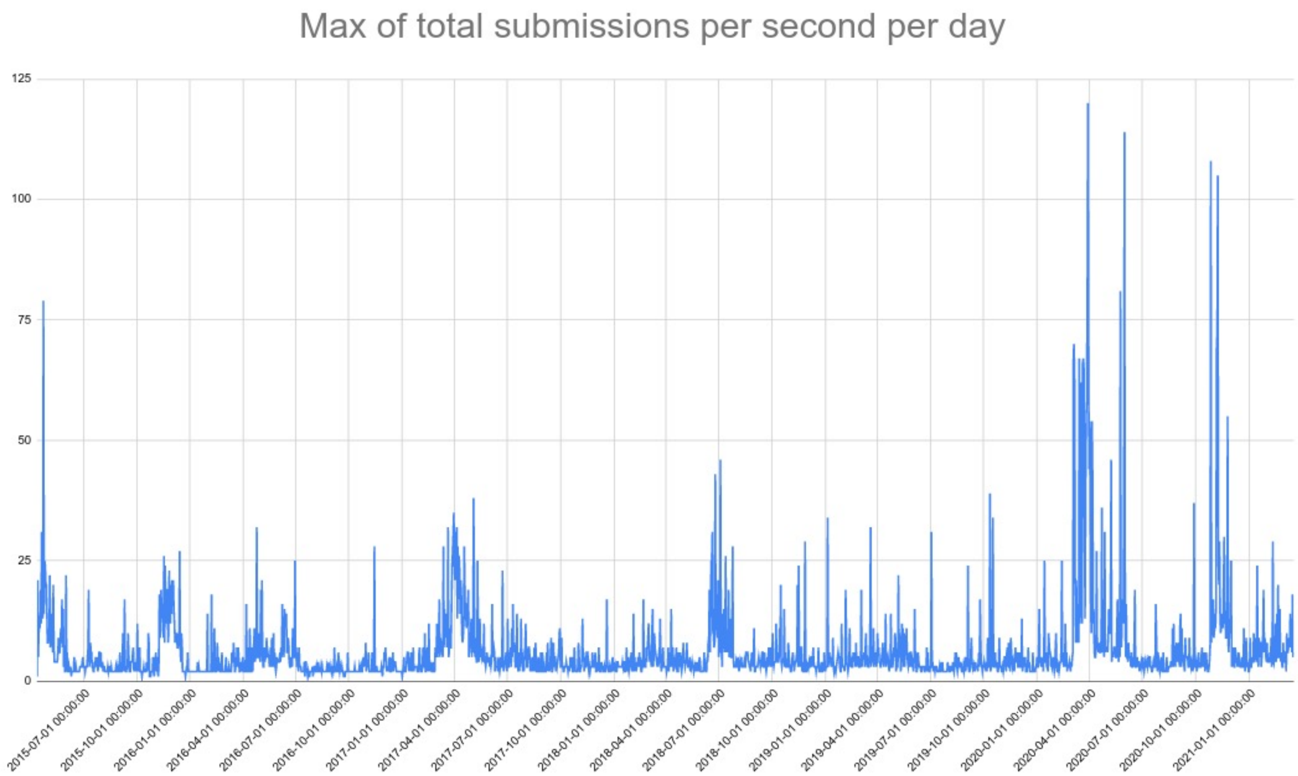
Requirements Analysis
Past Performance



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Identified Requirements

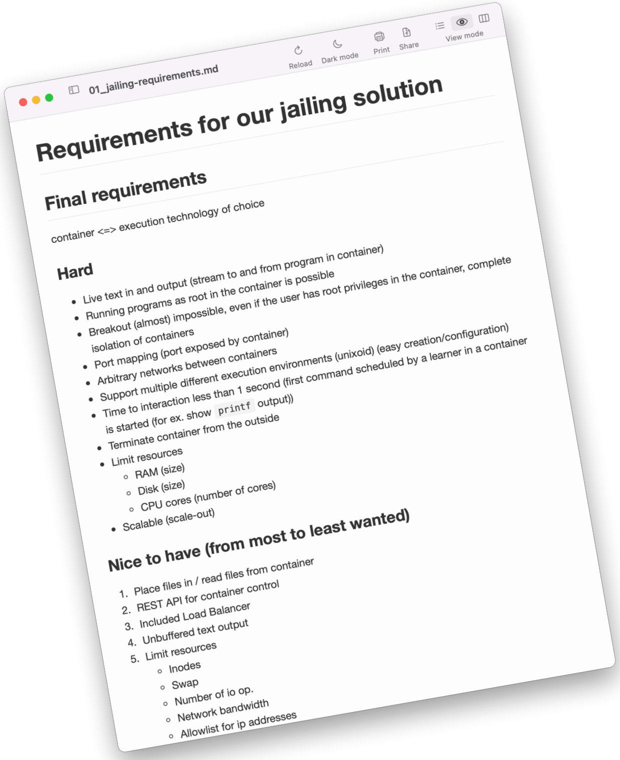
1. **Interactivity**
   - Synchronous channel between the execution and the users’ web browser
   - Real-time code executions
2. **Scalability**
   - Current system handles up to 120 execution requests per second
   - Mean execution time less than 10 seconds per execution
3. **Flexibility**
   - Compatibility to containerd ecosystem (e.g., through a Dockerfile)

Identified Requirements

1. **Interactivity**
2. **Scalability**
3. **Flexibility**

- Limit resources
  - CPU: Wall clock time, CPU shares
  - RAM
  - Network access
- Isolation between different executions
- Desired: Network orchestration with multiple nodes

Evaluation
Criteria


01_jailing-requirements.md

Reload Dark mode Print Share View mode

Requirements for our jailing solution

Final requirements

container <=> execution technology of choice

Hard

- Live text in and output (stream to and from program in container)
- Running programs as root in the container is possible
- Breakout (almost) impossible, even if the user has root privileges in the container, complete isolation of containers
- Port mapping (port exposed by container)
- Arbitrary networks between containers
- Support multiple different execution environments (unixoid) (easy creation/configuration)
- Time to interaction less than 1 second (first command scheduled by a learner in a container is started (for ex. show `printf` output))
- Terminate container from the outside
- Limit resources
  - RAM (size)
  - Disk (size)
  - CPU cores (number of cores)
- Scalable (scale-out)

Nice to have (from most to least wanted)

1. Place files in / read files from container
2. REST API for container control
3. Included Load Balancer
4. Unbuffered text output
5. Limit resources
   - Inodes
   - Swap
   - Number of io op.
   - Network bandwidth
   - Allowlist for ip addresses

- **Features**
  - Attach to stdout, stderr, stdin
  - Allow superuser access within the execution
- **Metrics**
  - Startup time
  - RAM / CPU usage
- **Technical details**
  - Maintenance and management
  - Isolation technologies and security implications

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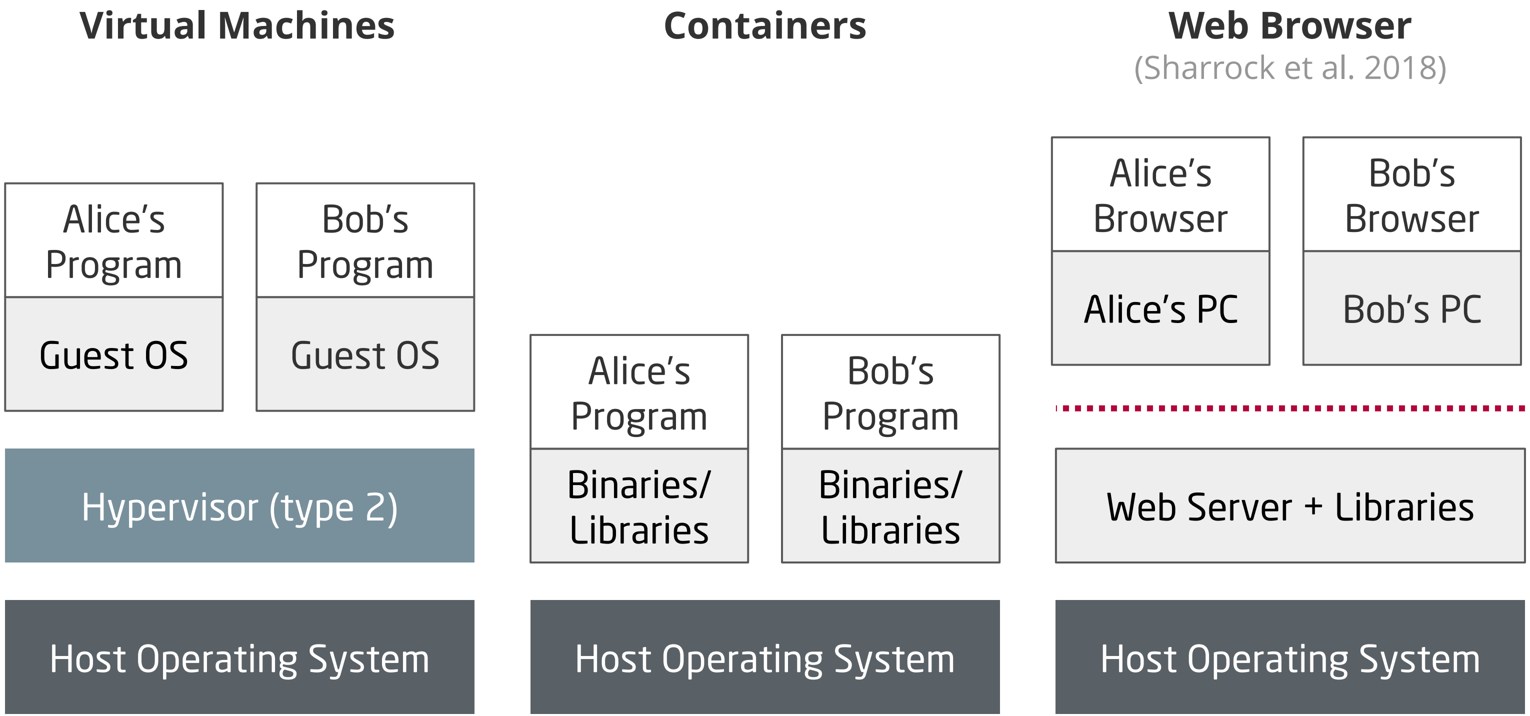
Related Work
Execution Environments



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Execution Environments

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Excluded by the requirements	Approved for performance evaluation
Pouch	docker
rkt	Firecracker
LXC	katacontainers
VirtualBox	

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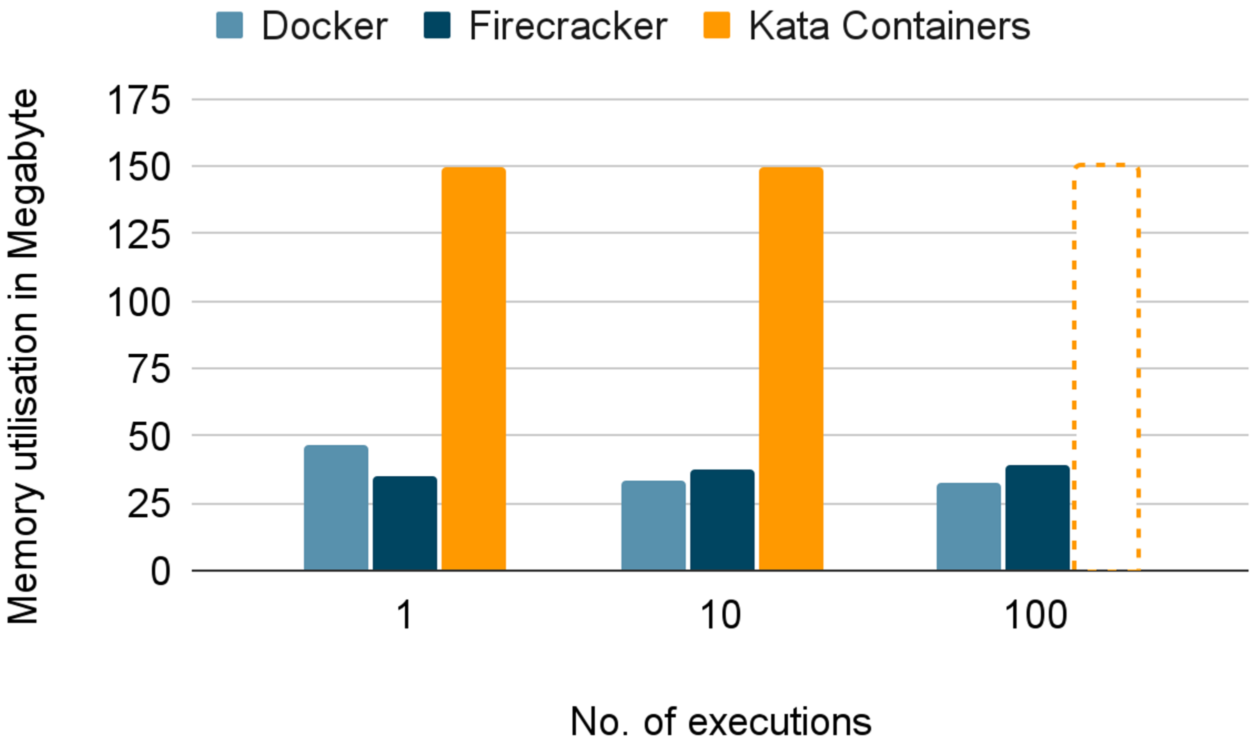
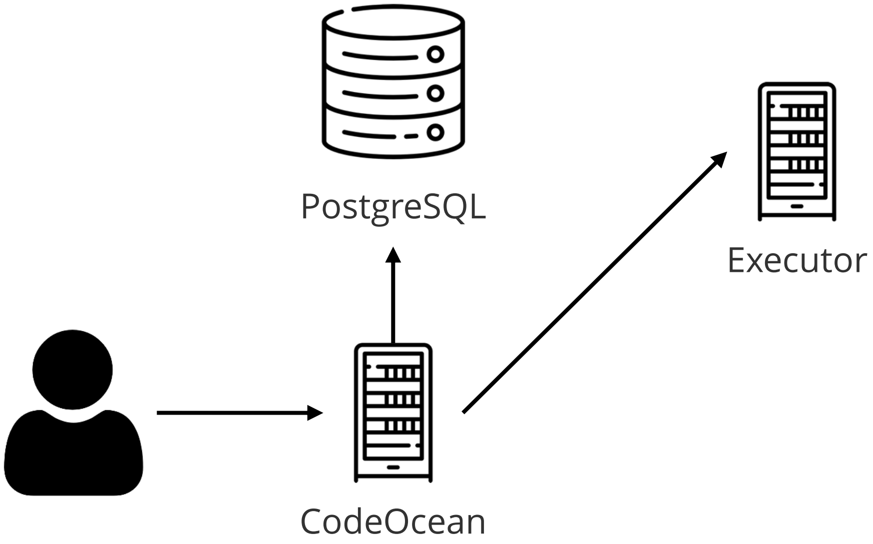
Execution Environments
Startup time

Execution Environments
Memory usage



Requirement Evaluation
Scalability



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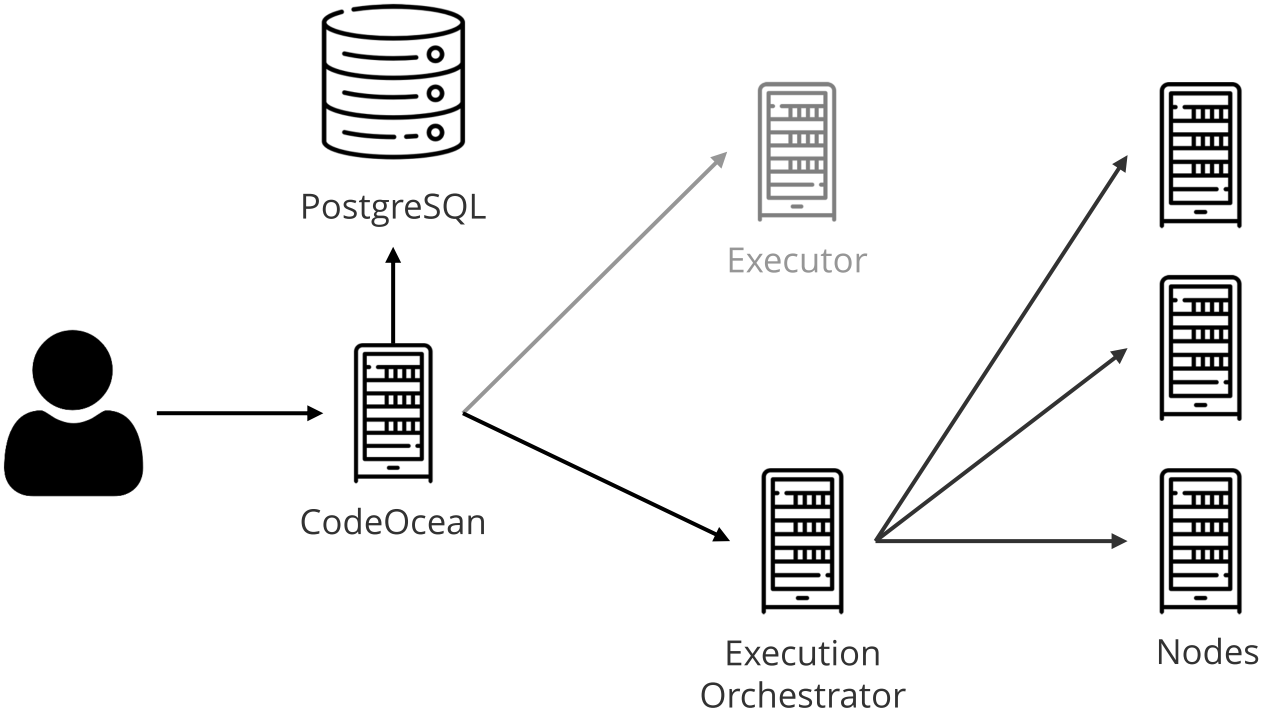
Requirement Evaluation
Scalability



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Execution Orchestrators

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Excluded by the requirements

fission

Kubeless

RANCHER

OPENFAAS

Knative

Approved for performance evaluation

Nomad

kubernetes

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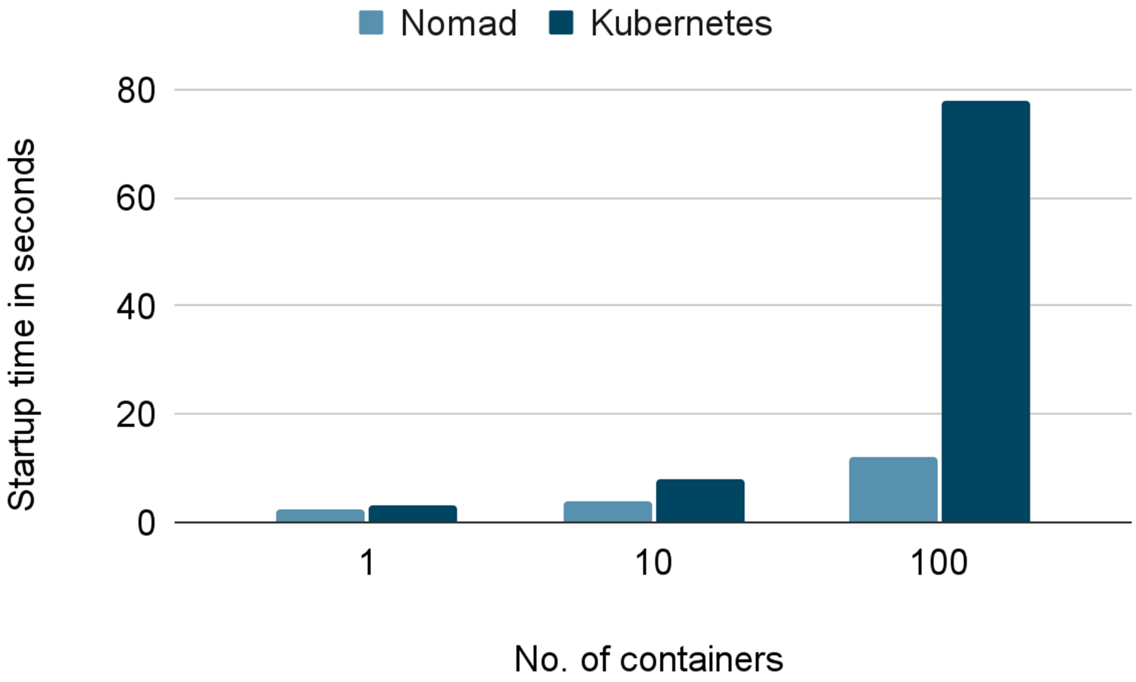
Execution Orchestrators
Nomad vs Kubernetes



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Evaluation
Comparison

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Environments

Firecracker

docker

katacontainers

Orchestrators

Nomad

kubernetes

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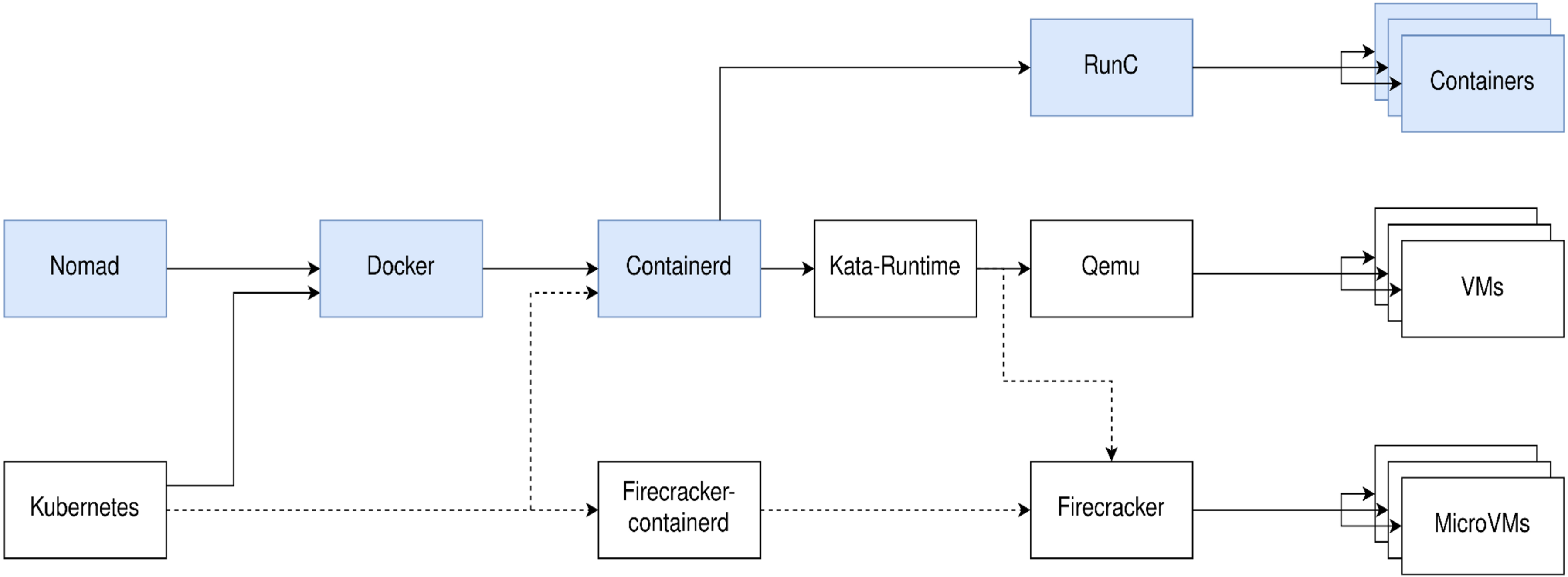
Requirement Evaluation
Flexibility



Evaluation
Comparison

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Environments

Firecracker

docker

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Orchestrators

Nomad

kubernetes

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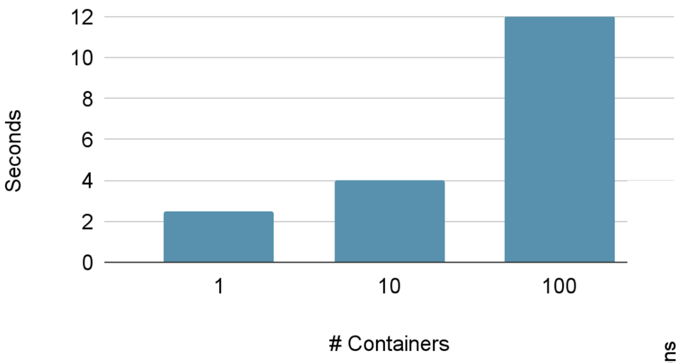
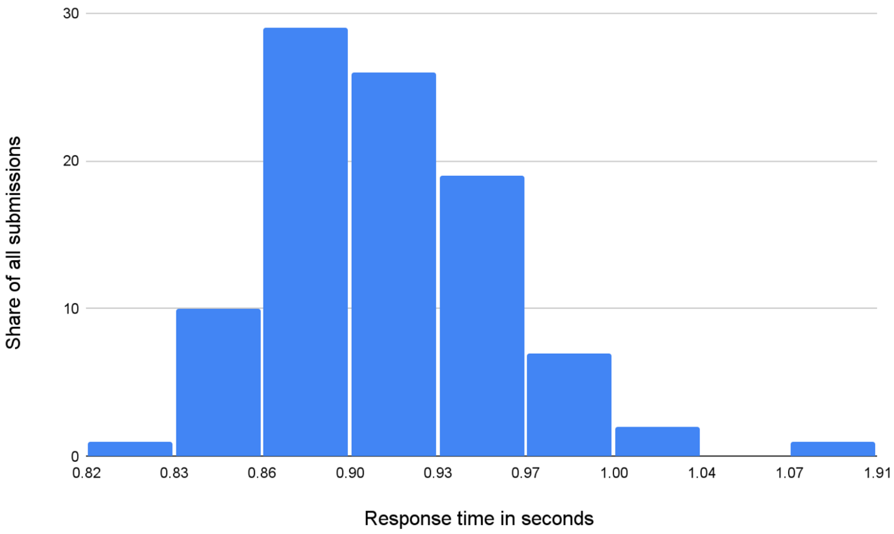
Evaluation
Prewarming

Startup time





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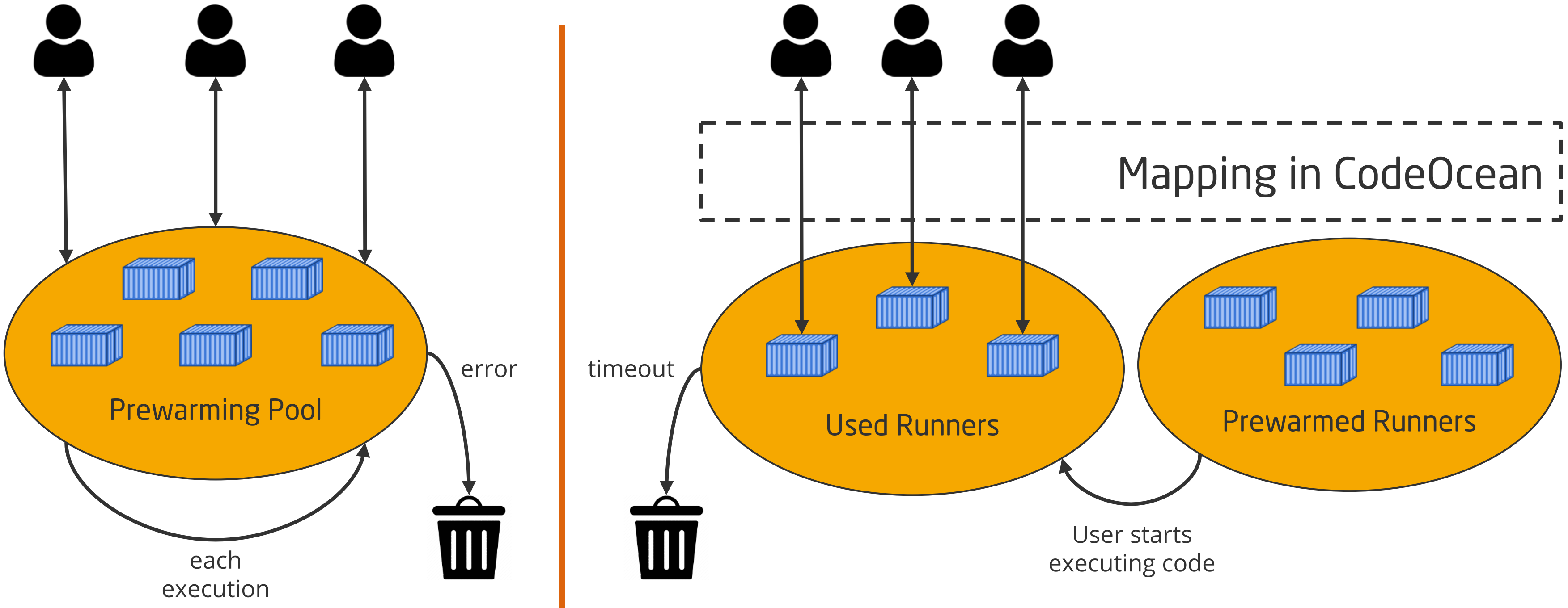
Evaluation
Container Reusing



Old

New

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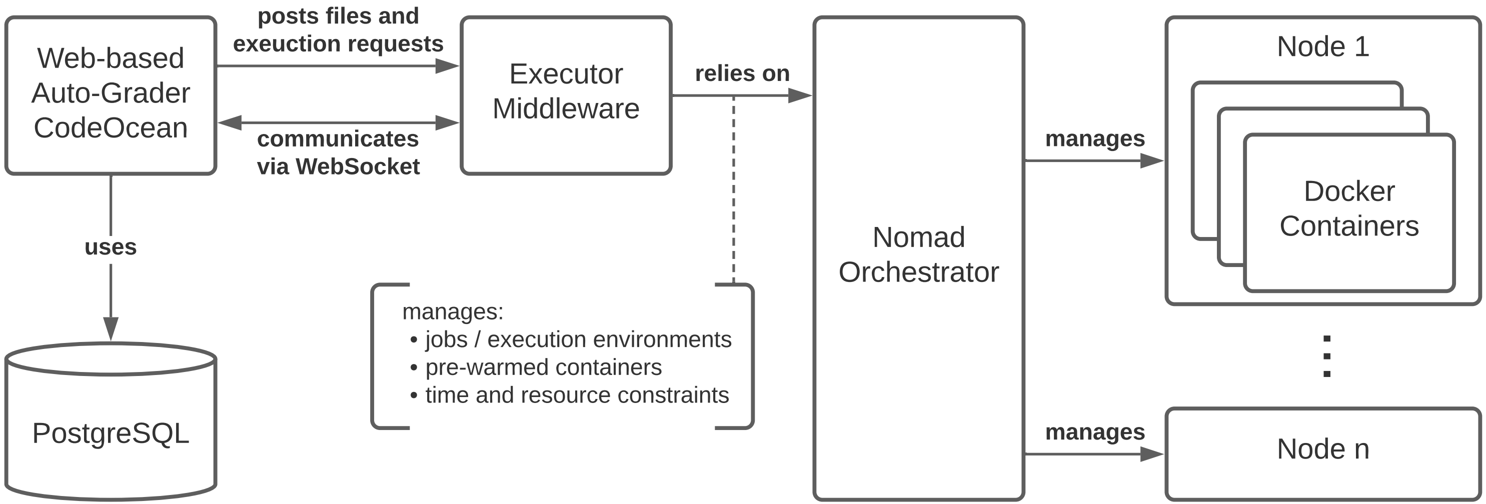
New System Architecture



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Future Work

- Integration of hardware resources
  - GPU for machine learning exercises (for teaching purposes at HPI)
  - Raspberry PI for embedded smart home courses on openHPI
- Networking scenarios
  - Multi-node setup and VPN access
- Long lasting executions
  - Debugging
- Pre-warming strategies and Function-as-a-Service (FaaS)
- Comparison of programming languages and their security concepts for system components (especially the executor middleware)

Conclusion

- Identification of three main requirements:

Interactivity	Scalability	Flexibility

- Evaluation of several containerization and orchestration technologies:

Docker
Firecracker > Kata Containers

Nomad > Kubernetes

- Executor middleware abstracts from
  - container management and pre-warming
  - specific interface of the orchestrator

→ **Result: Scalable and more secure architecture for execution environments**

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