OSNABRÜCK UNIVERSITY

Using Genode as Enabler for Research on Modern Operating Systems

Bruxelles, February 5, 2023

Michael Müller

About me

- Studied computer science at TU Dortmund
- Graduated with MSc in 2018
- Since 2018 **PhD student** at ESS Group **at Osnabrück University**
- **Full-time research assistant** in the **MxKernel** project **at** TU Dortmund and **Osnabrück University**
- Focused on **research** for **many-core OSes**

Assumptions from the past … that shaped today's OSes

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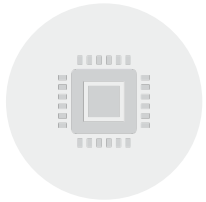

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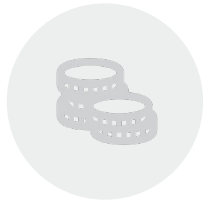

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The memory architecture is uniform

I/O is slower than the CPU

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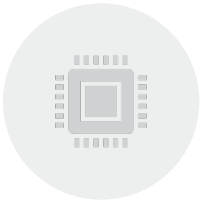

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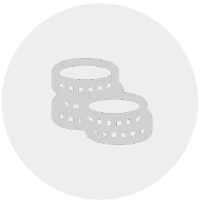

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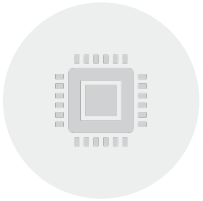

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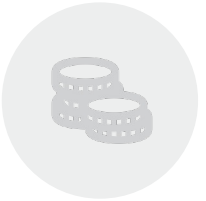

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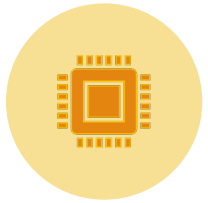

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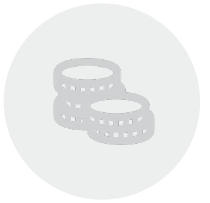

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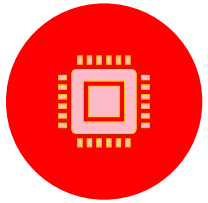

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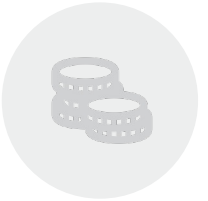

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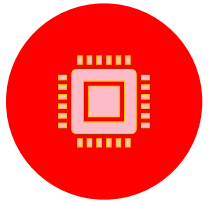

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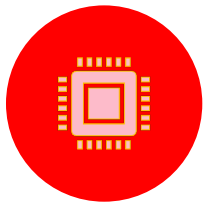

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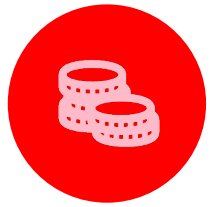

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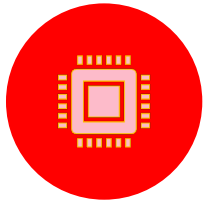

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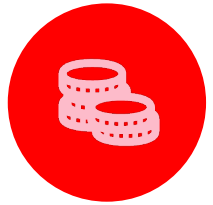

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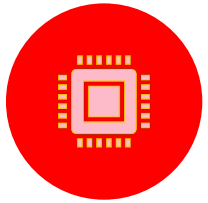

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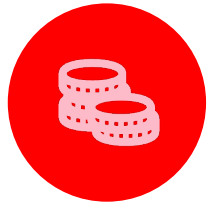

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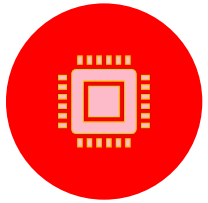

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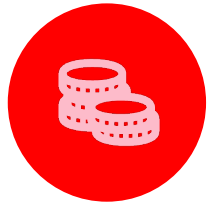

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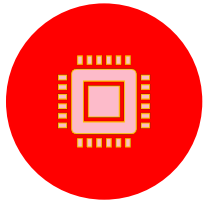

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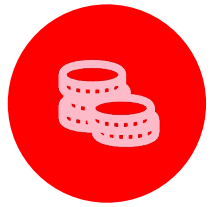

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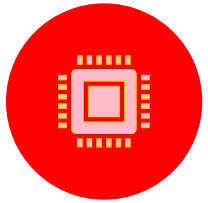

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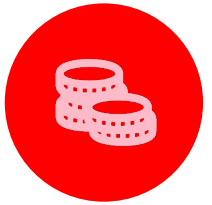

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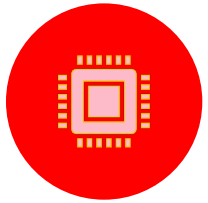

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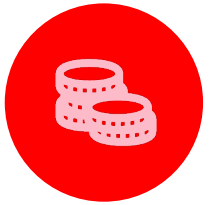

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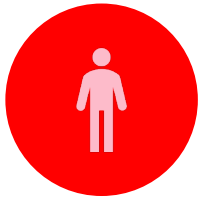
The truth about modern computers



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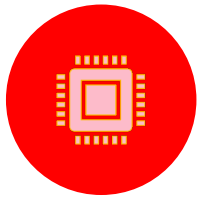

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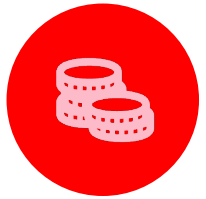

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⇒ We need further research on operating systems

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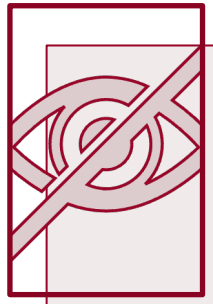

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- hinder implementing drivers
- hamper in-depth evaluation

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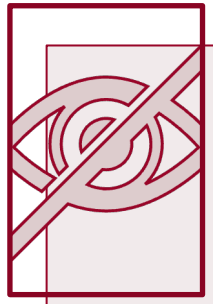

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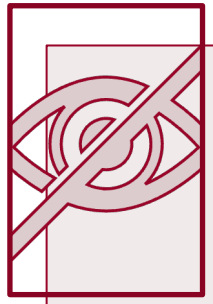

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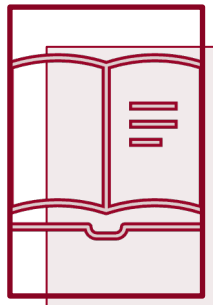

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- leads to reverse-engineering

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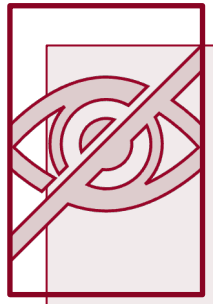

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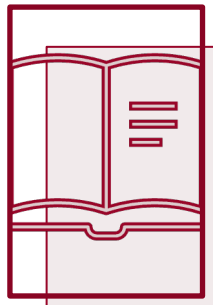

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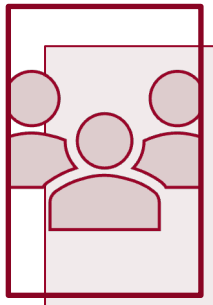

Lack of man-power

- puts tight limit on what can be done
- may endanger project success

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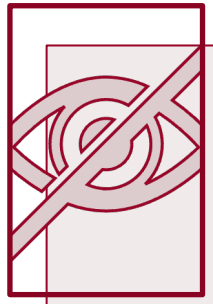

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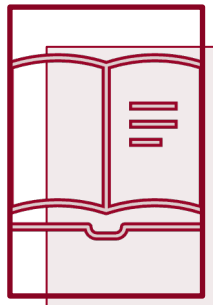

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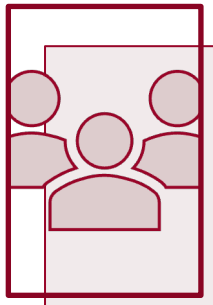

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Complexity of modern hardware

- increases effort needed for OS engineering and implementation
- Impede comprehension

SO, WHAT DO RESEARCHERS DO?

Workarounds and Tweaks

[1] Firestone, D. et al. 2018. Azure Accelerated Networking: SmartNICs in the Public Cloud. *15th USENIX Symposium on Networked Systems Design and Implementation, NSDI 2018, Renton, WA, USA, April 9-11, 2018* (2018), 51–66.
[2] Fried, J., Ruan, Z., Ousterhout, A. and Belay, A. 2020. Caladan: Mitigating Interference at Microsecond Timescales. *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020.* (2020), 281–297.
[3] Høiland-Jørgensen, T., Brouer, J.D., Borkmann, D., Fastabend, J., Herbert, T., Ahern, D. and Miller, D. 2018. The eXpress data path: fast programmable packet processing in the operating system kernel. *Proceedings of the 14th International Conference on emerging Networking EXperiments and Technologies* (New York, NY, USA, Dec. 2018), 54–66.
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[9] Lin, J., Patel, K., Stephens, B.E., Sivaraman, A. and Akella, A. 2020. PANIC: A High-Performance Programmable NIC for Multi-tenant Networks. *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020.* (2020), 243–259.
[10] Mogul, J.C. 2003. TCP offload is a dumb idea whose time has come. *Proceedings of the 9th conference on Hot Topics in Operating Systems - Volume 9* (USA, May 2003), 5.
[11] Pirelli, S. and Candea, G. 2020. A Simpler and Faster NIC Driver Model for Network Functions. *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020.* (2020), 225–241.
[12] Ren, Y., Min, C. and Kannan, S. 2020. CrossFS: A Cross-layered Direct-Access File System. *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020.* (2020), 137–154.
[13] Rizzo, L. 2012. netmap: A Novel Framework for Fast Packet I/O. *2012 USENIX Annual Technical Conference, Boston, MA, USA, June 13-15, 2012* (2012), 101–112.
[14] Rommel, F., Dietrich, C., Friesel, D., Köppen, M., Borchert, C., Müller, M., Spinczyk, O. and Lohmann, D. 2020. From Global to Local Quiescence: Wait-Free Code Patching of Multi-Threaded Processes. *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020.* (2020), 651–666.
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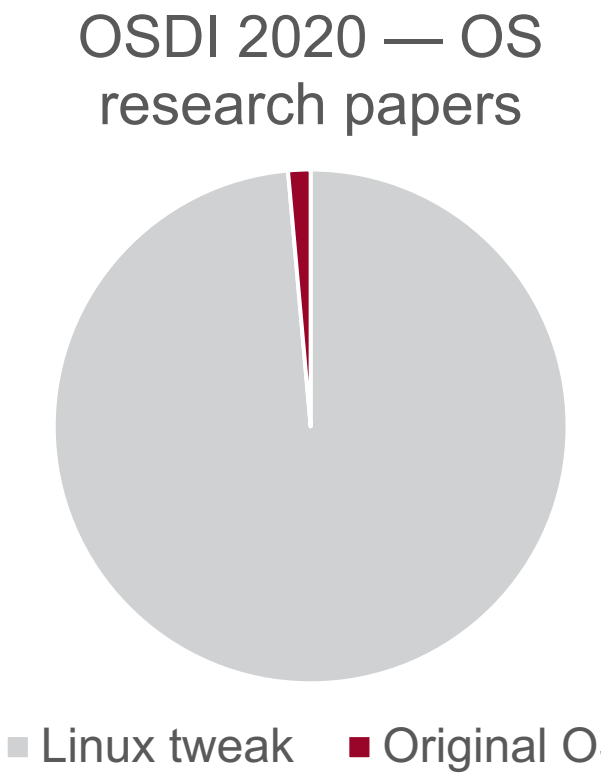
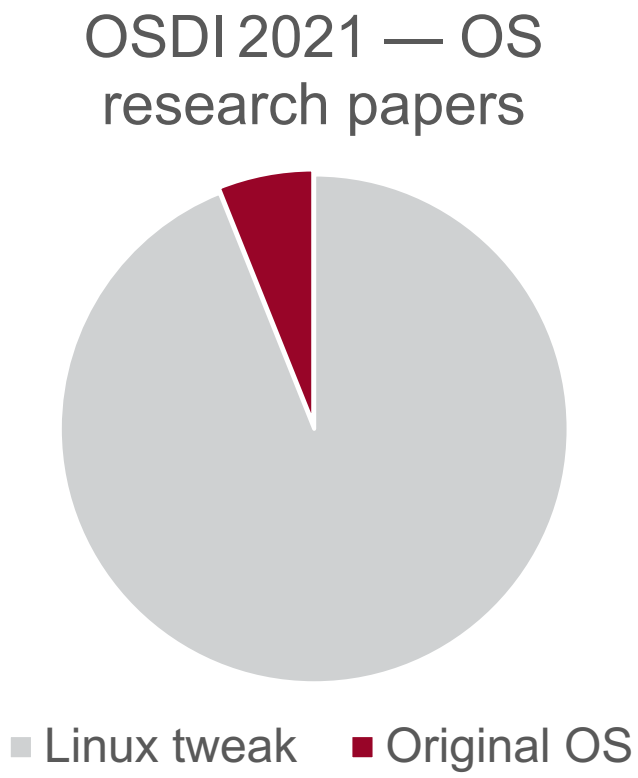
… wait, there are even more !

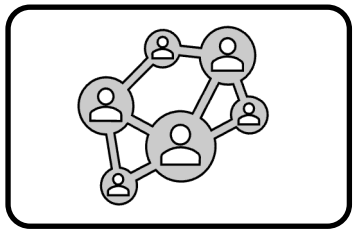
How OS research is done today … mostly





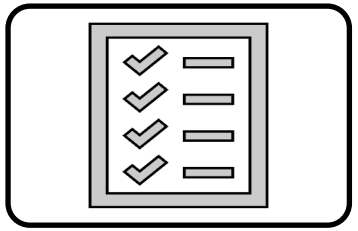
*Source: "**It's Time for Operating Systems to Rediscover Hardware**" -- Timothy Roscoe, USENIX ATC '21/OSDI '21 Joint Keynote*

Why hacking Linux isn't a good idea



Huge and complex code-base

- Increases effort needed



POSIX-compliance

- Limits OS abstractions and interfaces
- Significant changes may break user space

Moving target

- Constant maintenance required
- No maintenance ⇒ Extensions will break

Isn’t there something better?

Isn’t there something better?

… maybe some OS framework?

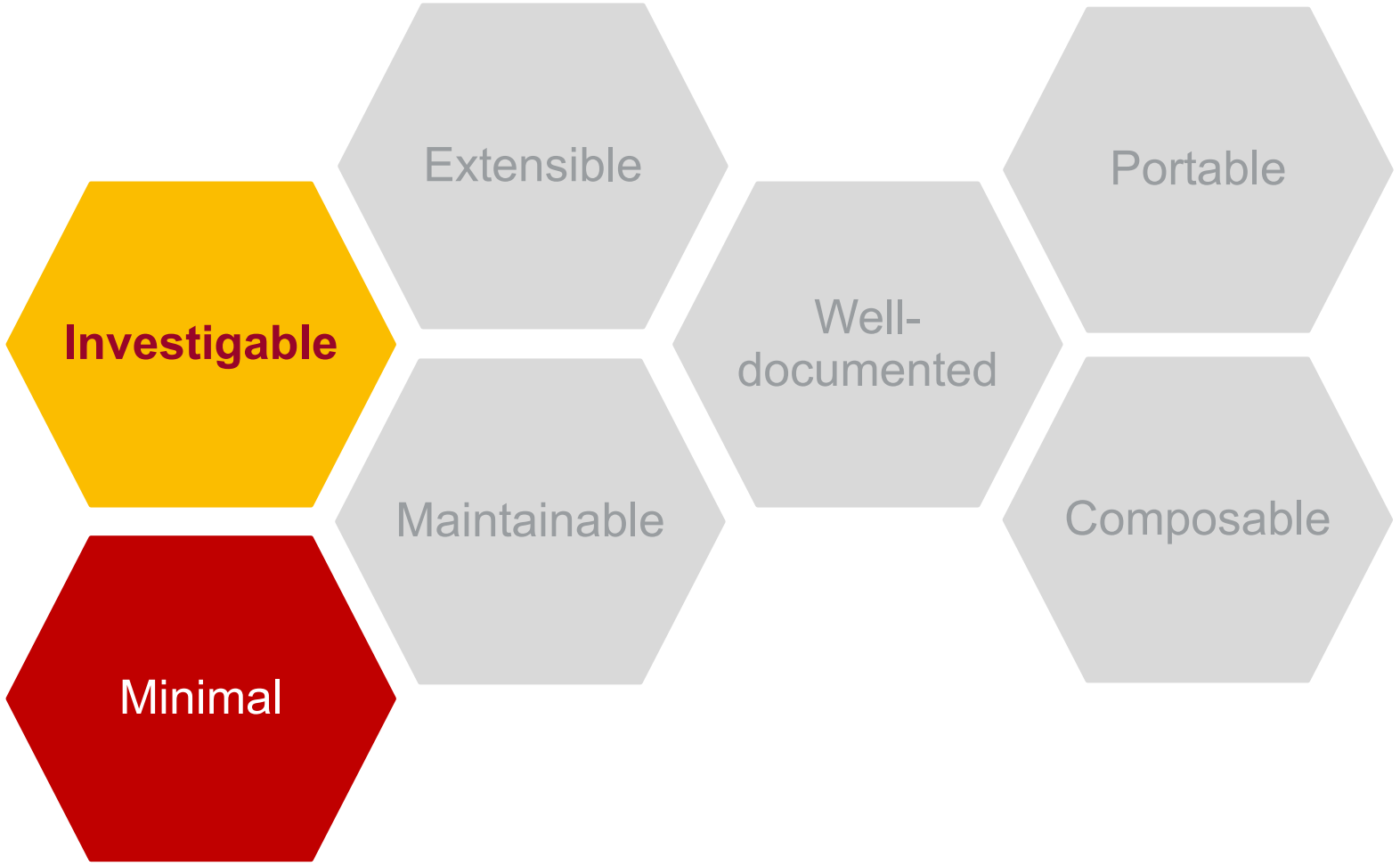
A framework for OS research shall be

A framework for OS research shall be

- Eases **understanding**
- Simplifies **changing** kernel primitives
- Helps **debugging**

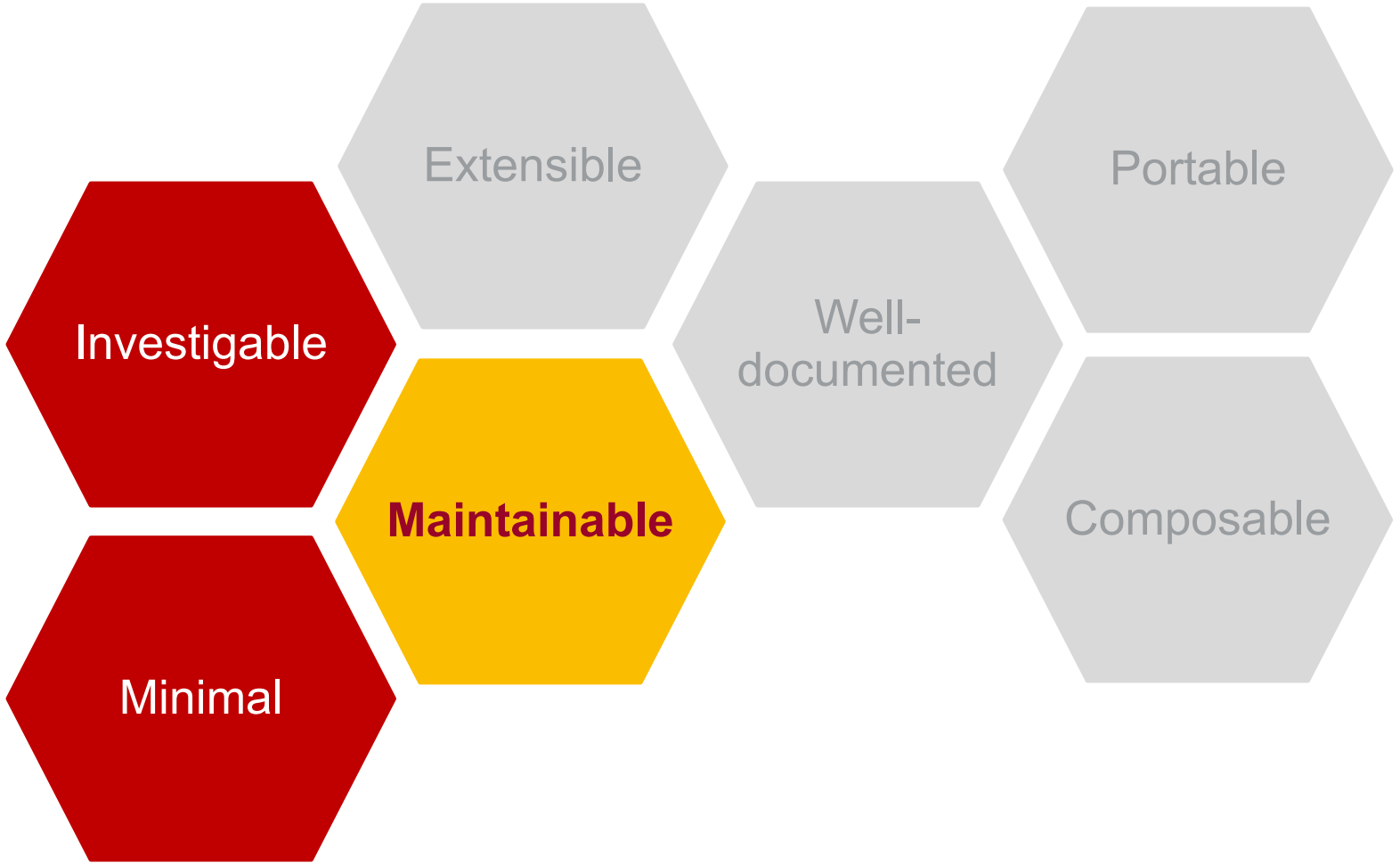
A framework for OS research shall be

- Necessary to **understand measurements**
- **Open Source** code base
- Provide **profiling** tools



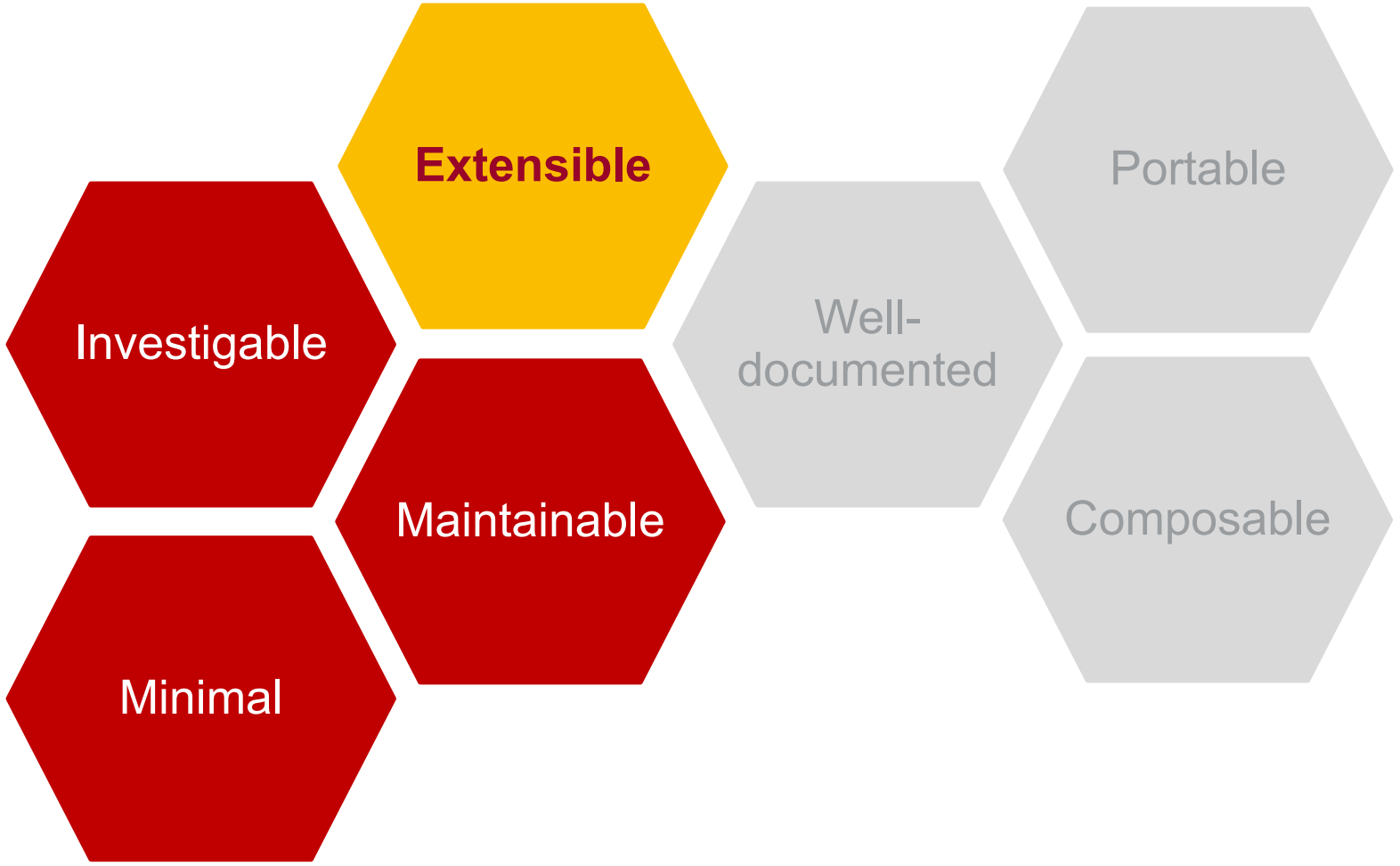
A framework for OS research shall be

- Regular **updates**
- But should **not break** fundamental interfaces
- If so, **only small** changes needed

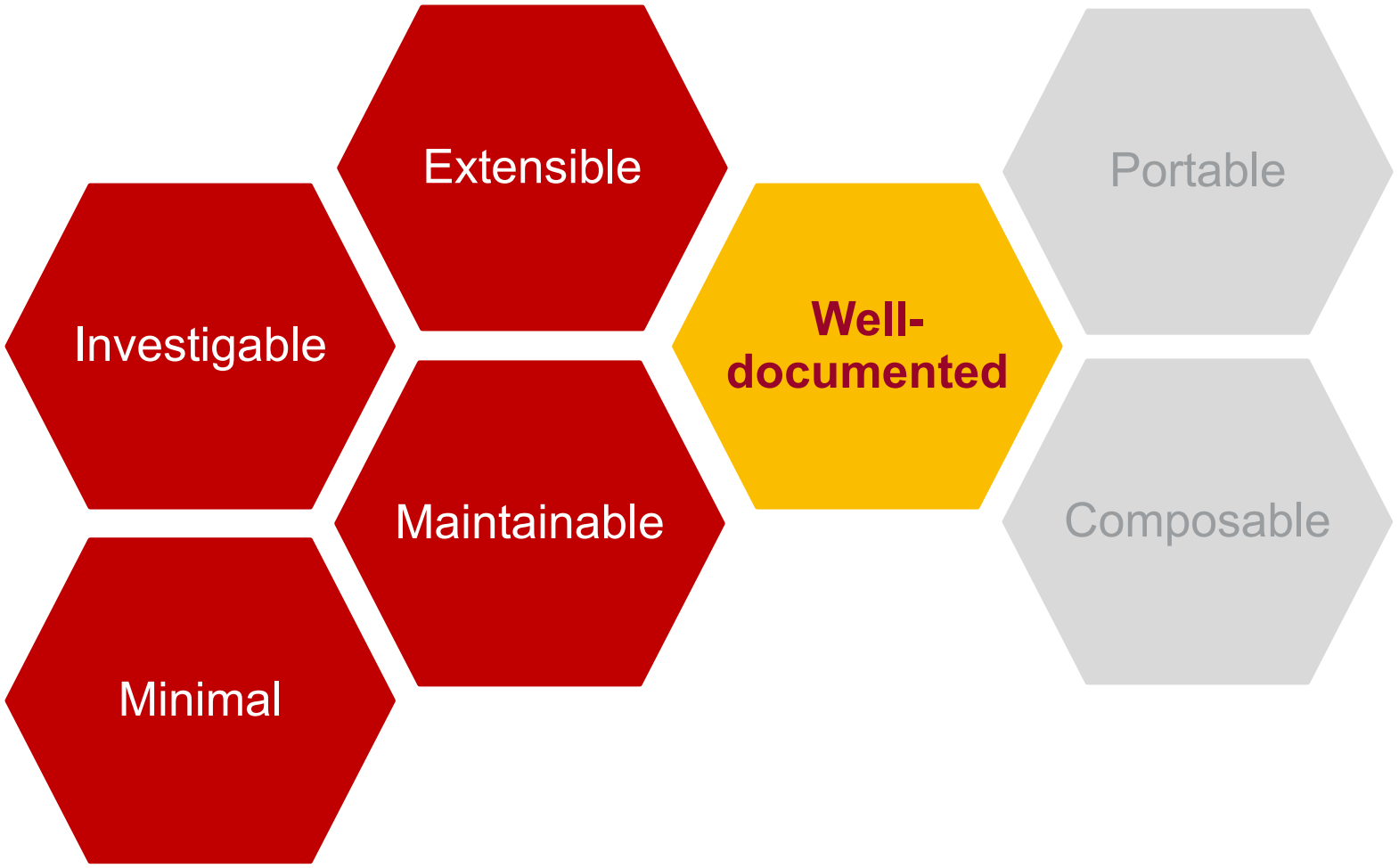


A framework for OS research shall be

- **Easy** to **write** new extensions
- **Separation** of concerns
- Well-defined **components**
- Well-defined **interface** between components

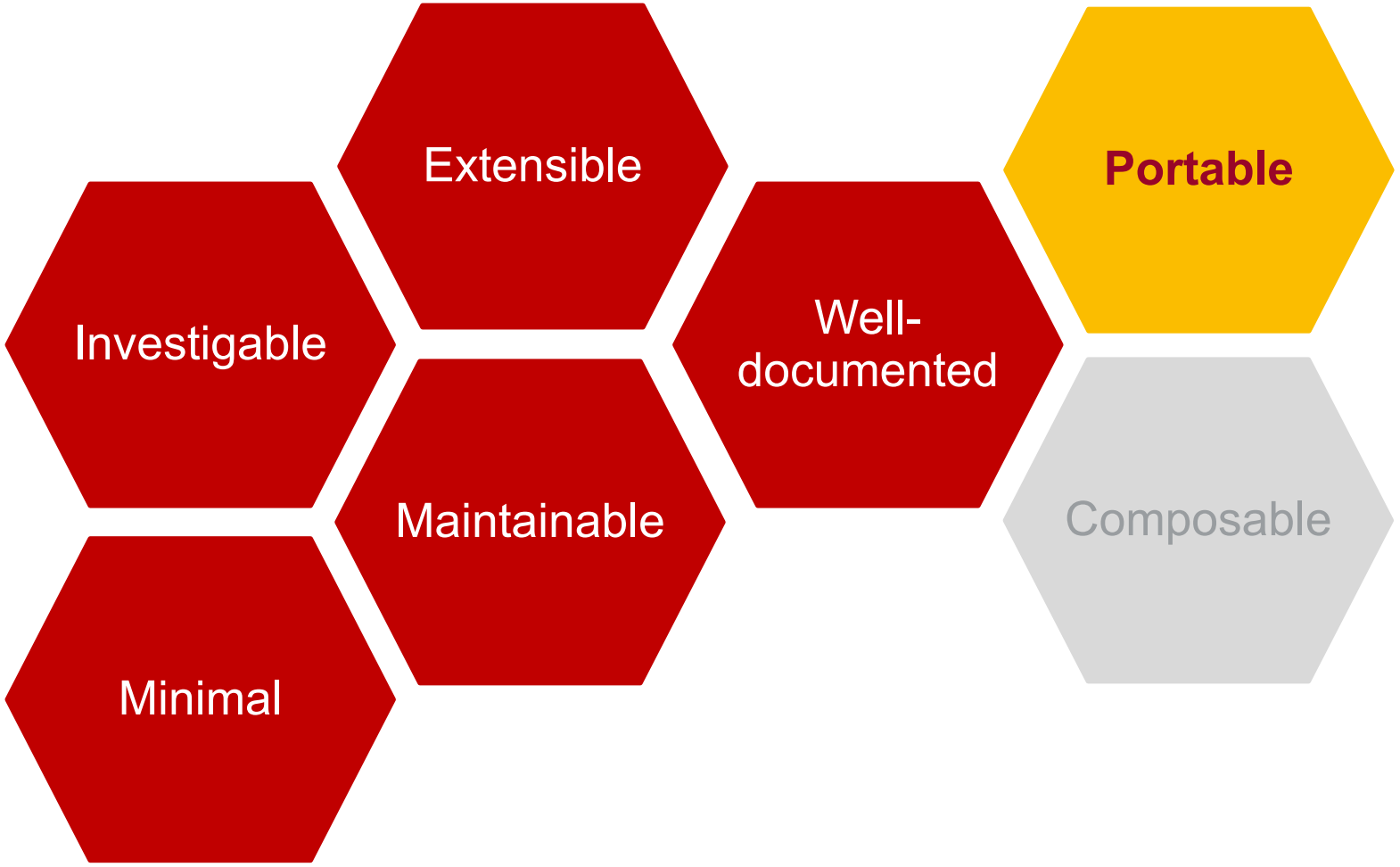


A framework for OS research shall be



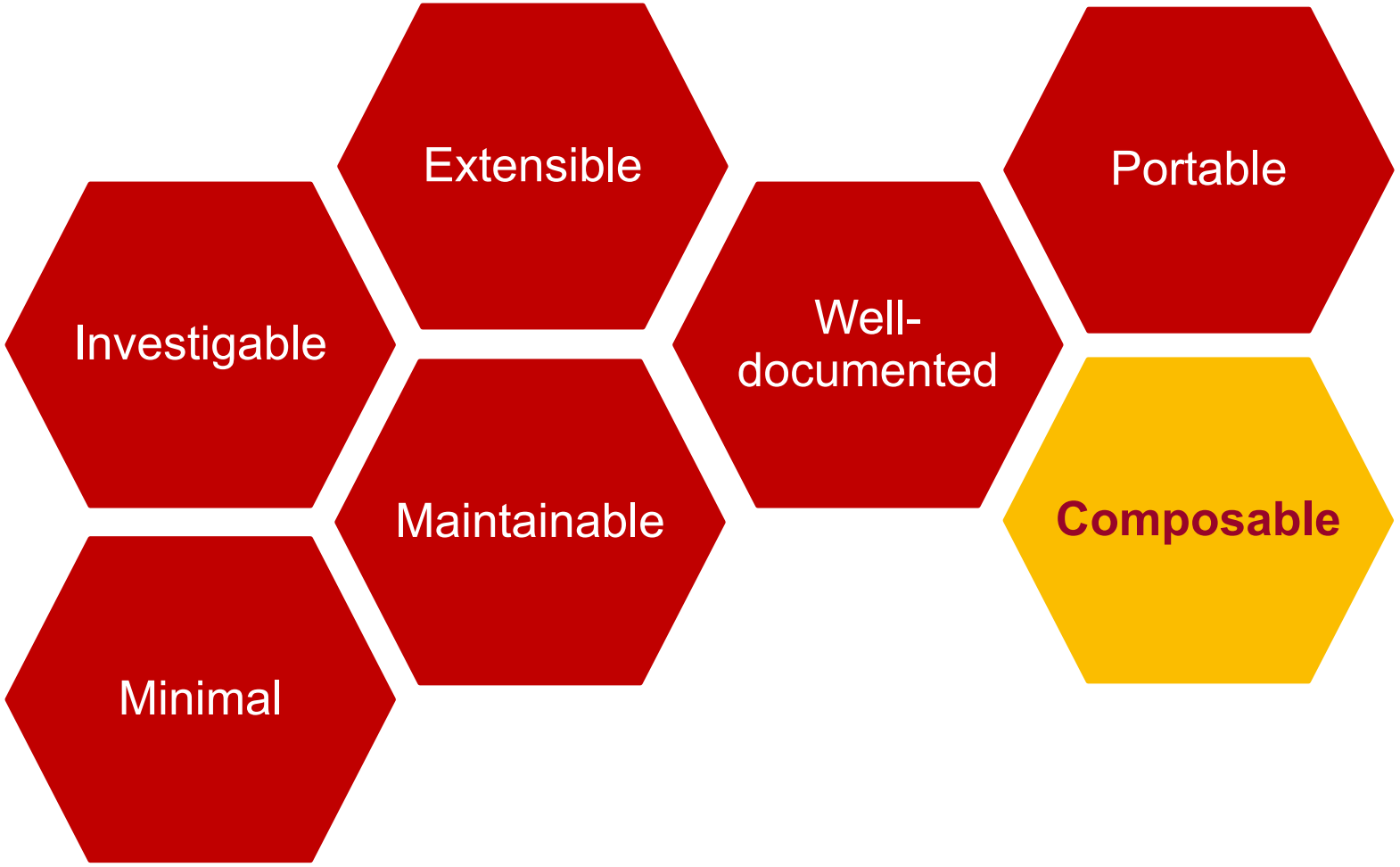
- **Ease** getting started
- **Provides** description of **important** components and **interfaces**
- **Ideally** a book
- **And** documented **code**

A framework for OS research shall be



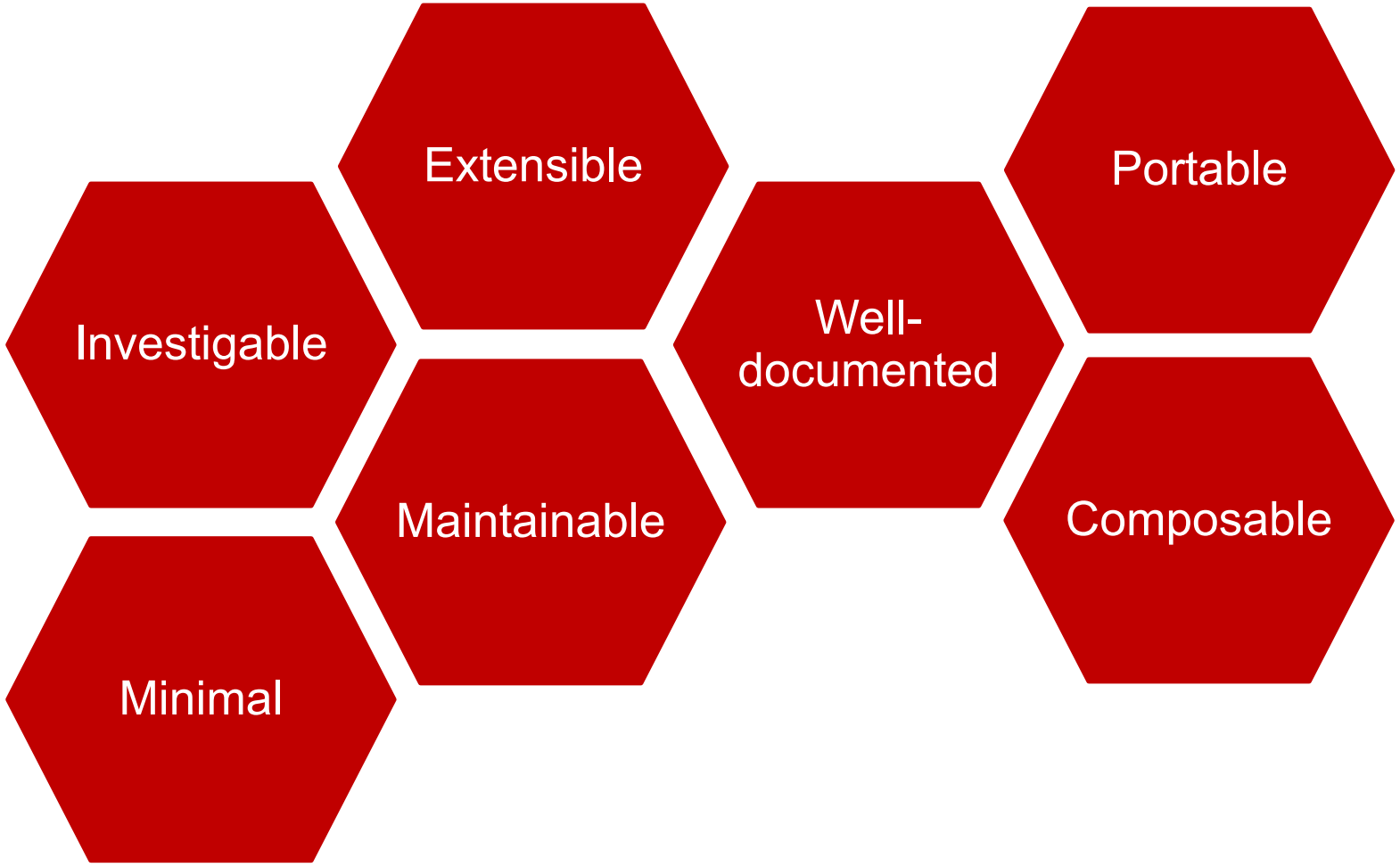
- **Future-proof**
- Enable **experimental** hardware
- **Support** Hardware/OS co-design

A framework for OS research shall be



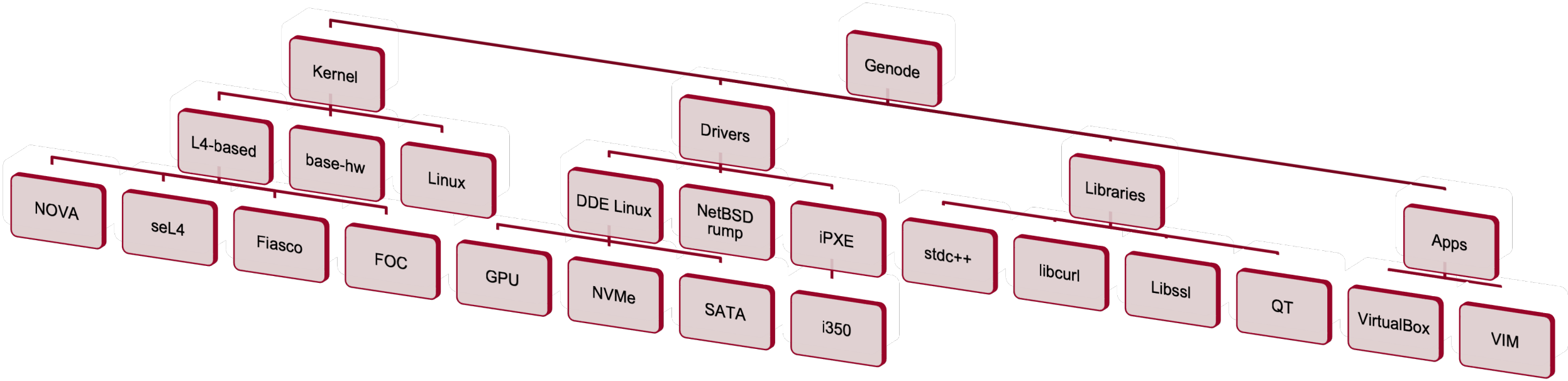
- **Replaceable** OS components
- Allow **different** OS interfaces **simultaneously**
- **Reusability** of drivers etc.

A framework for OS research shall be



A CANDIDATE FOR AN OS FRAMEWORK

The Genode OS Framework

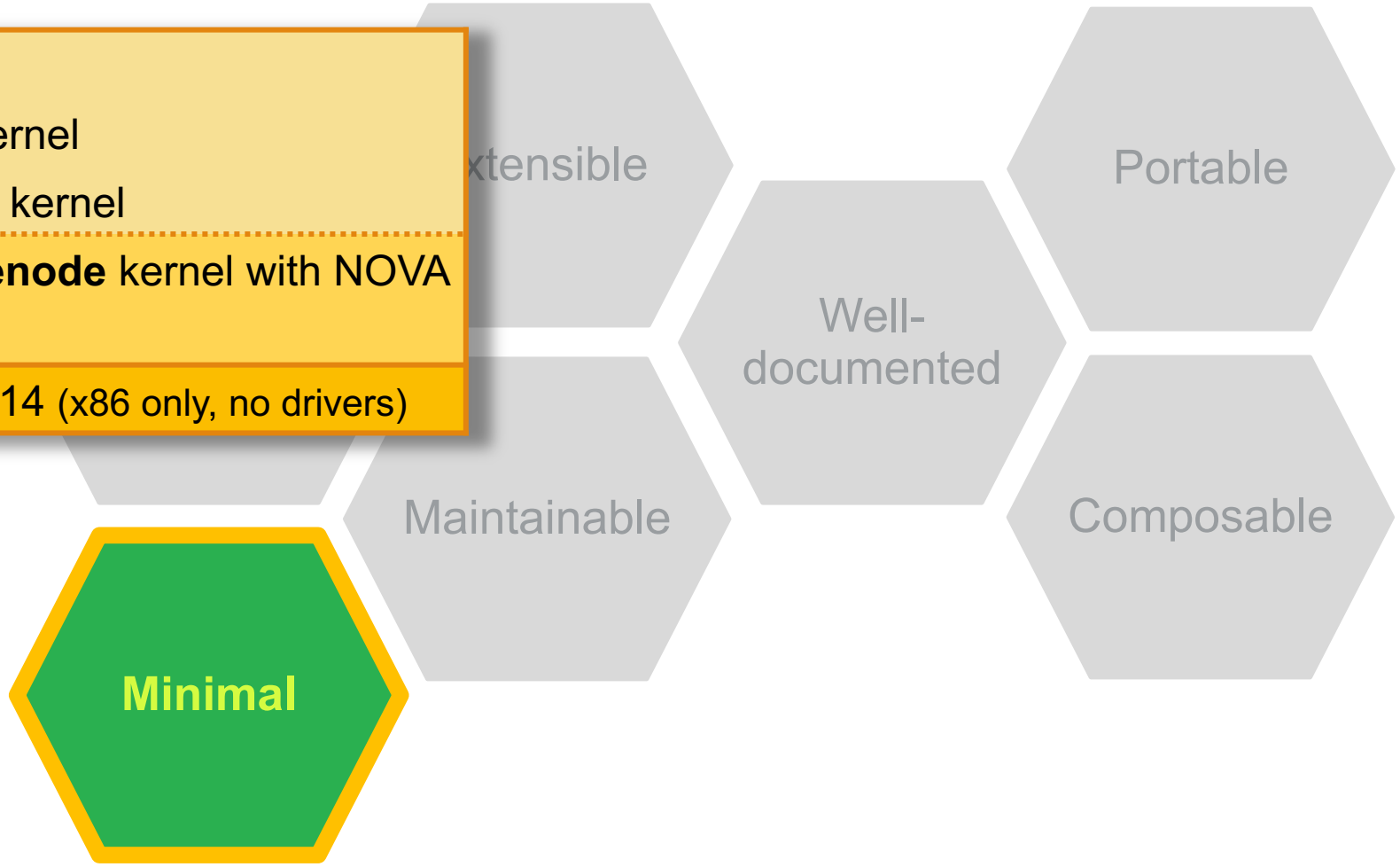


Does Genode fit the bill?

- complete
- almost complete
- satisfactory
- partial
- not yet
- not at all

Does Genode fit the bill?

31,918 LoC	for base
21,039 LoC	for NOVA kernel
18,211 LoC	for base-hw kernel
52,957 LoC	for basic **Genode** kernel with NOVA
50,129 LoC	base-hw
911,059 LoC	for **Linux** 4.14 (x86 only, no drivers)



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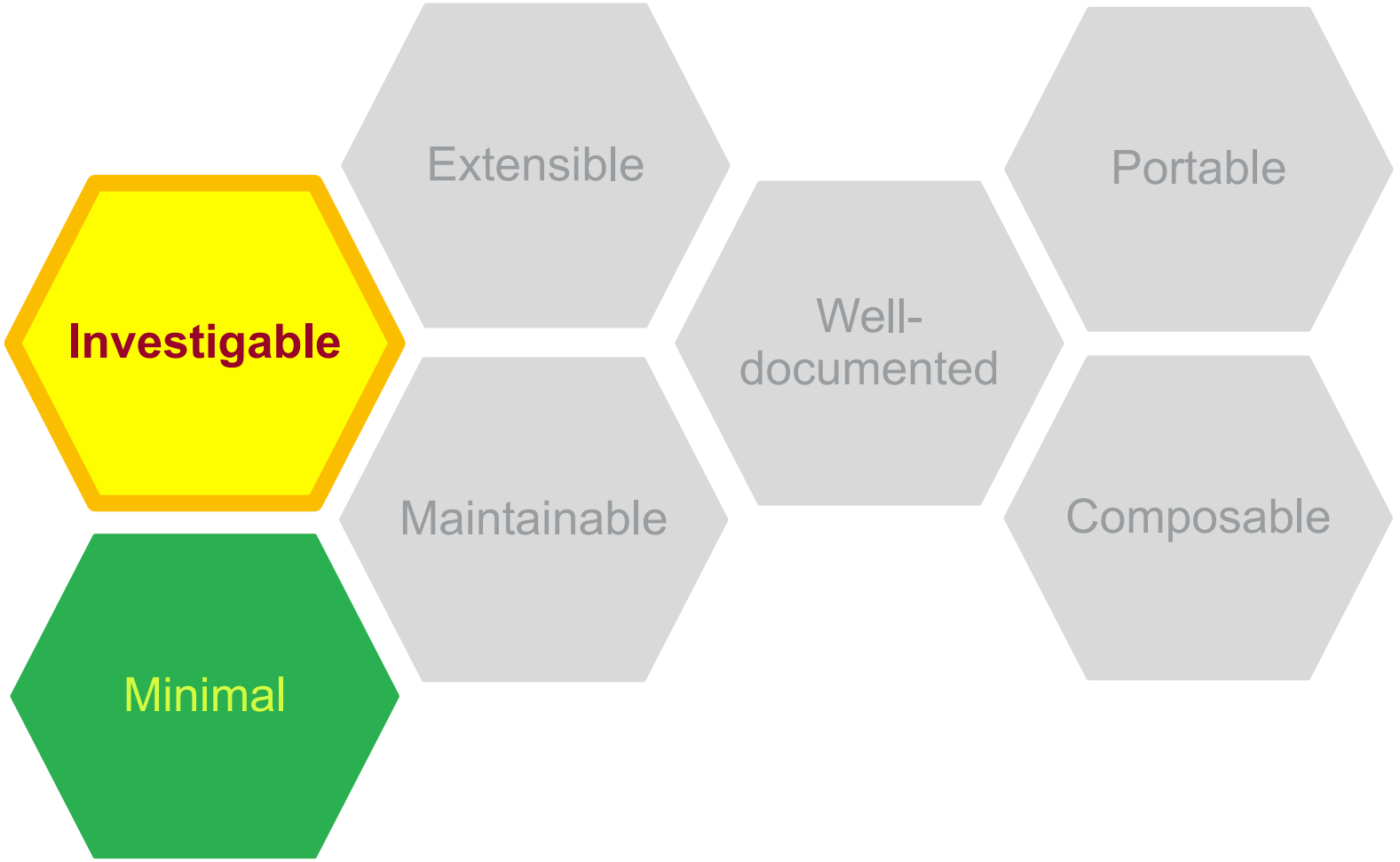
Does Genode fit the bill?

- Code Under **AGPL**
- Only **basic** tracing yet
- Only rudimentary **manual** profiling



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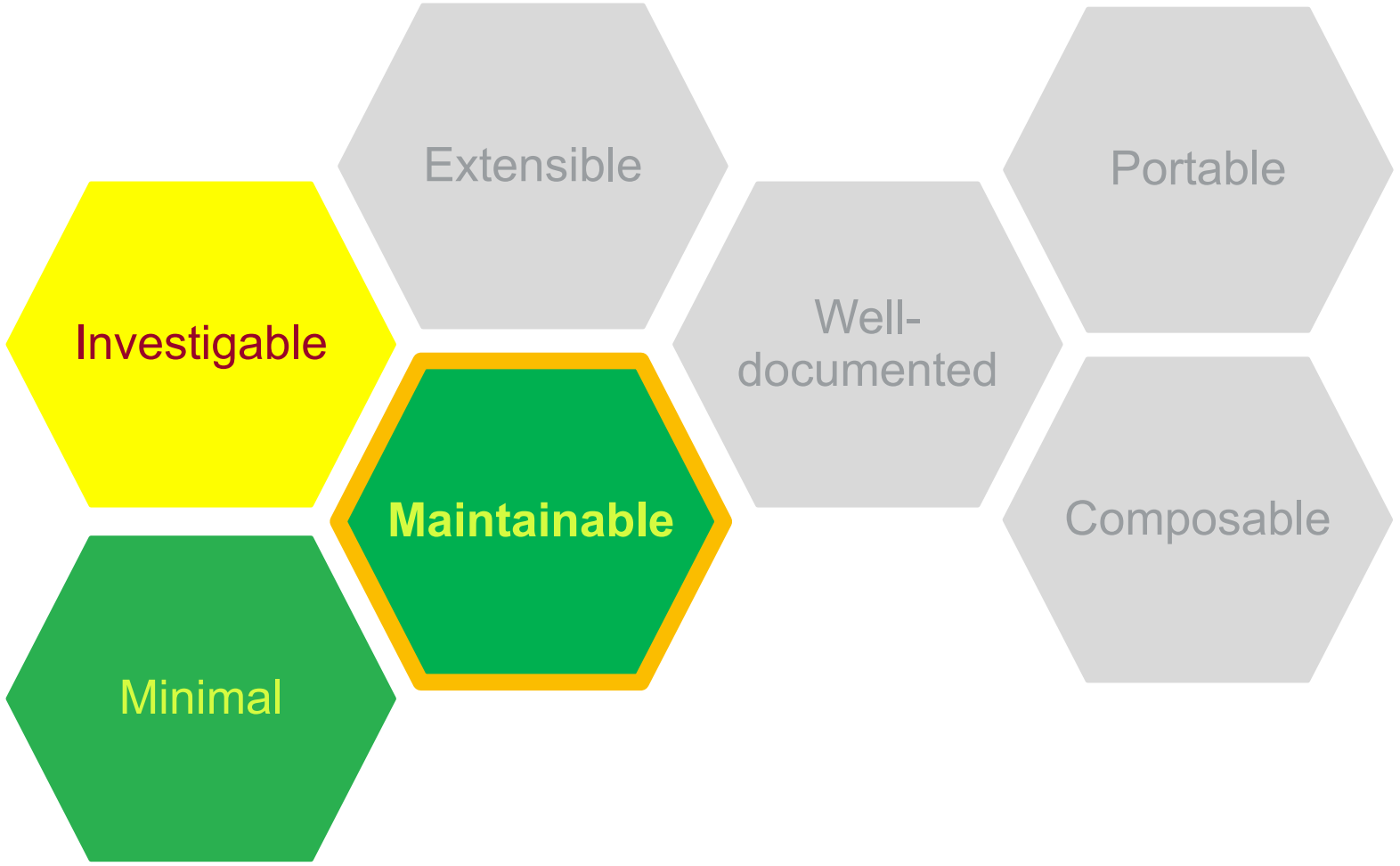
Does Genode fit the bill?

- **Quarterly** updates
- Mostly **minimal** changes to kernel API



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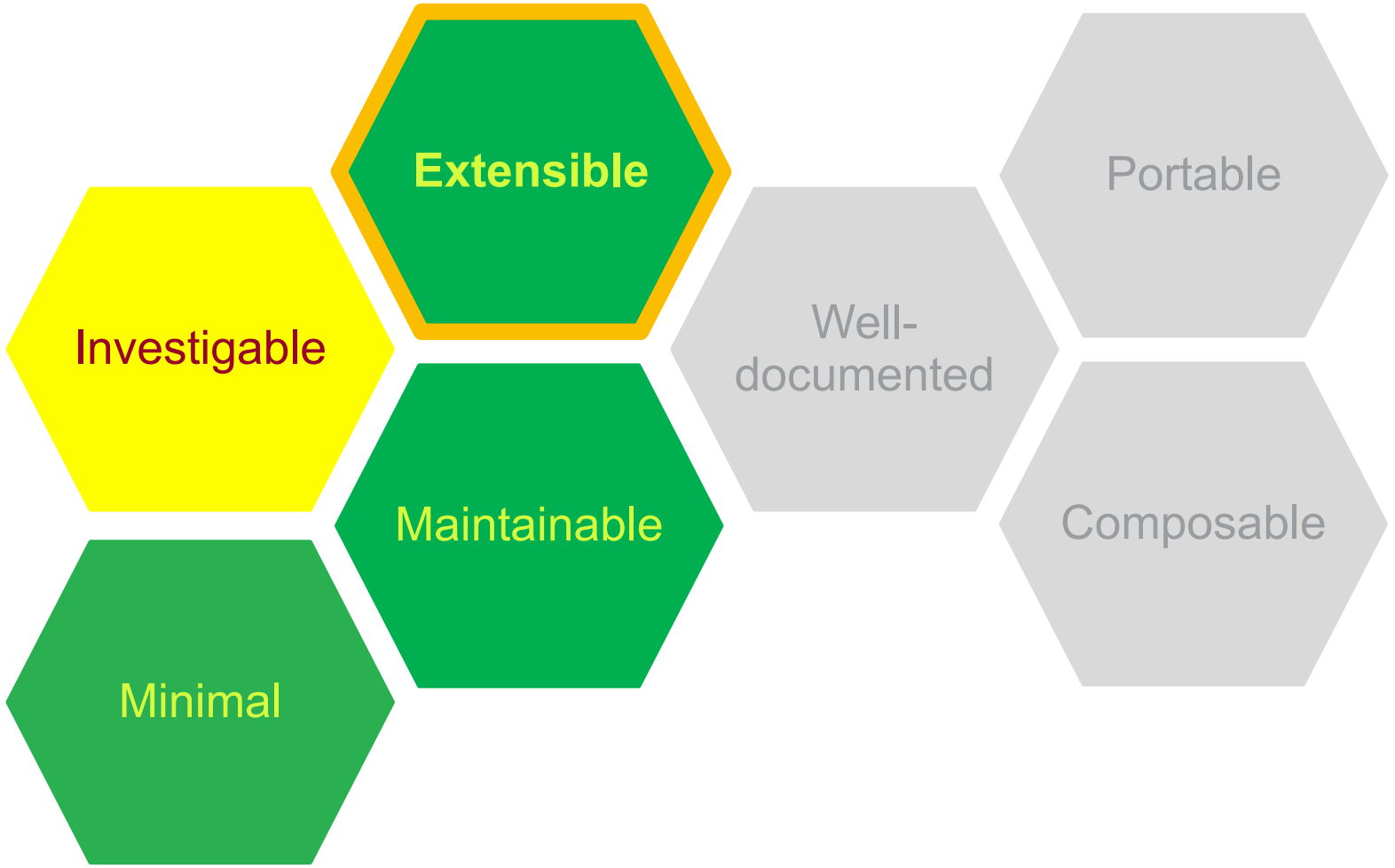
Does Genode fit the bill?

- **Clearly seperated** components
- **Well-defined** RPC interface
- **Minimal** requirements for new components



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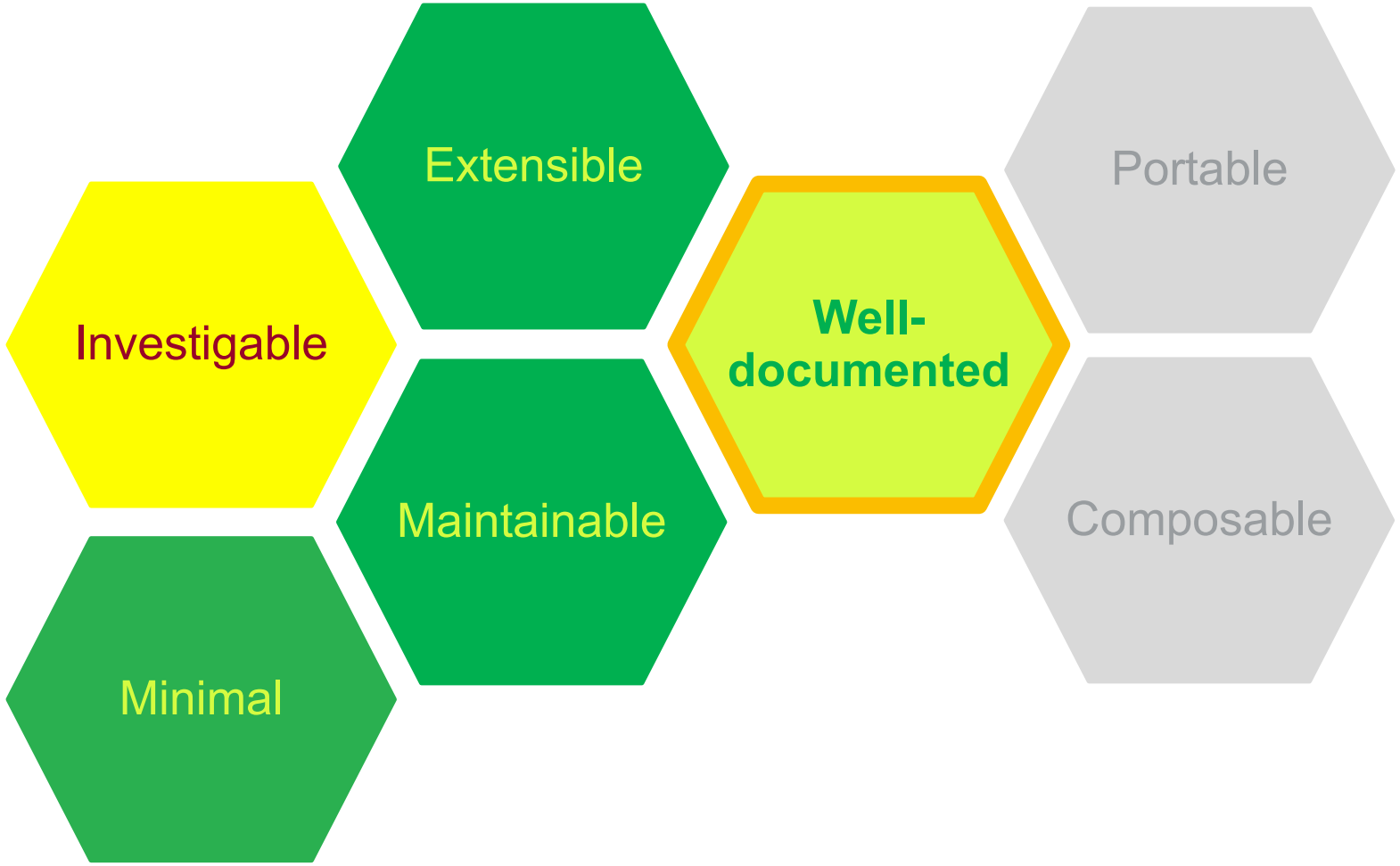
Does Genode fit the bill?

- **Book** “Genode Foundations”
- Extensive **changelog** for each release
- **FOSDEM** talks



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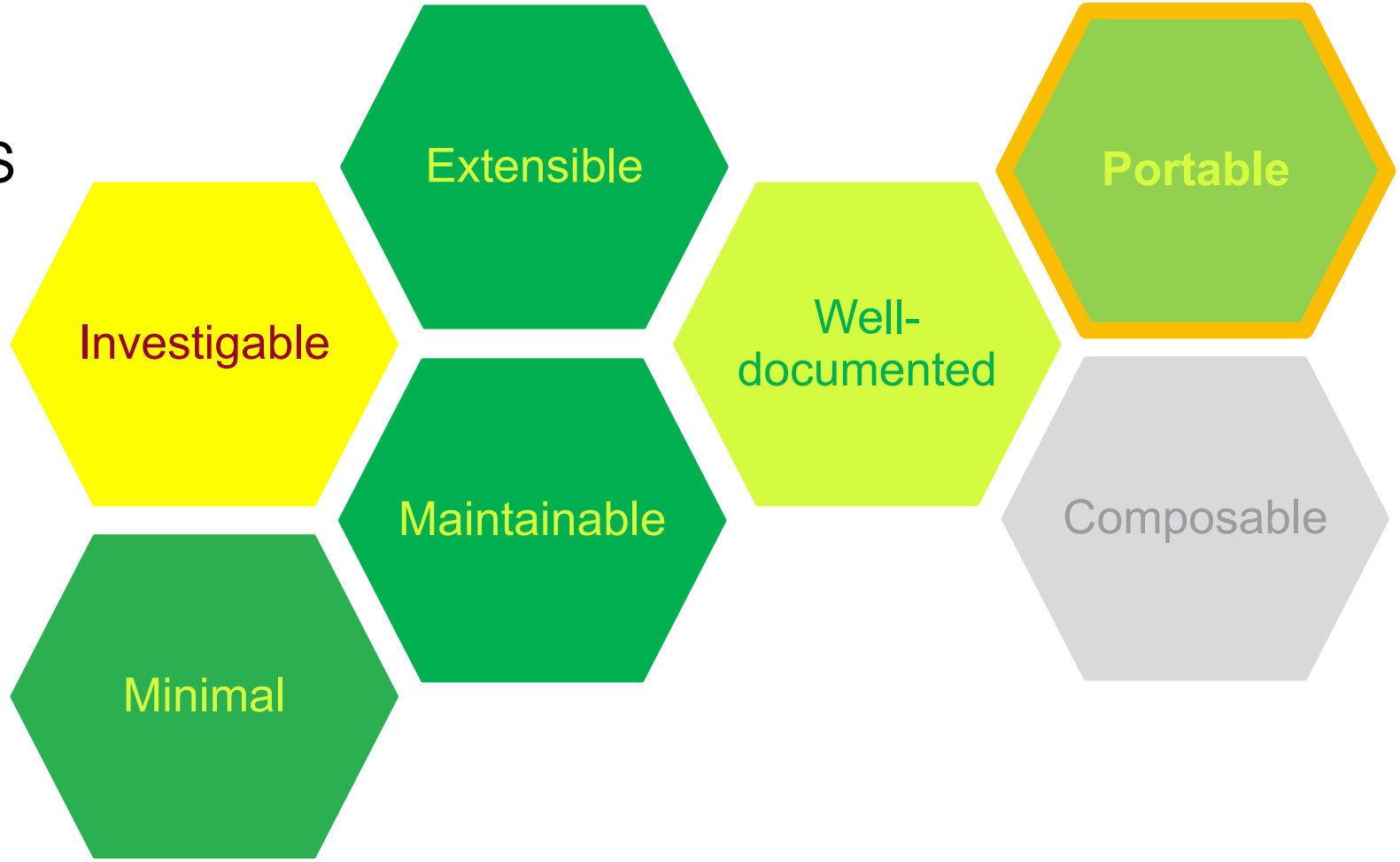
Does Genode fit the bill?

- **Strict seperation** of hardware platform and OS code
- **Generalized** concepts for hardware features



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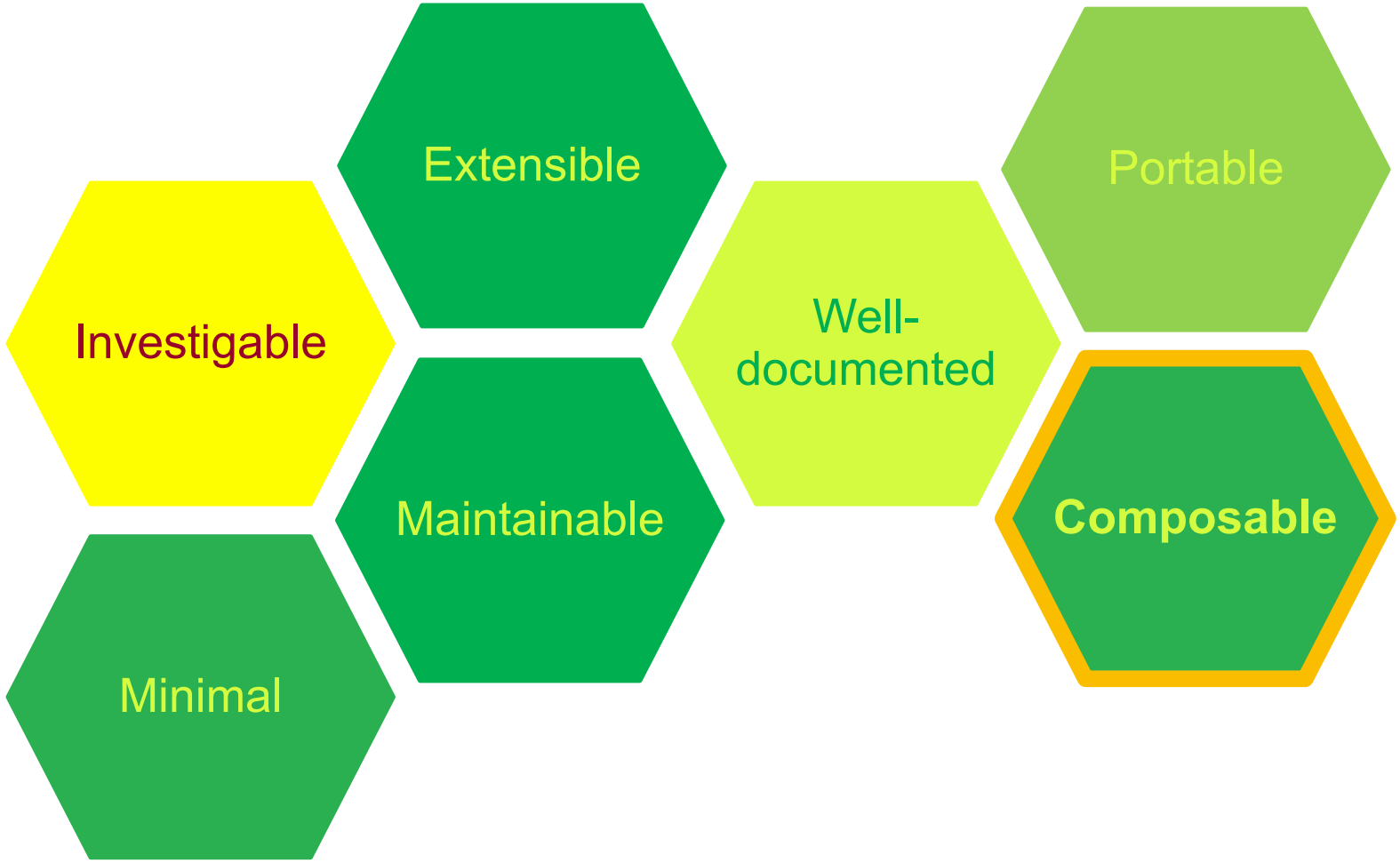
Does Genode fit the bill?

- **Component-based** architecture
- Own OS can be “**sculptured**”
- **Multiple** instances of a service possible



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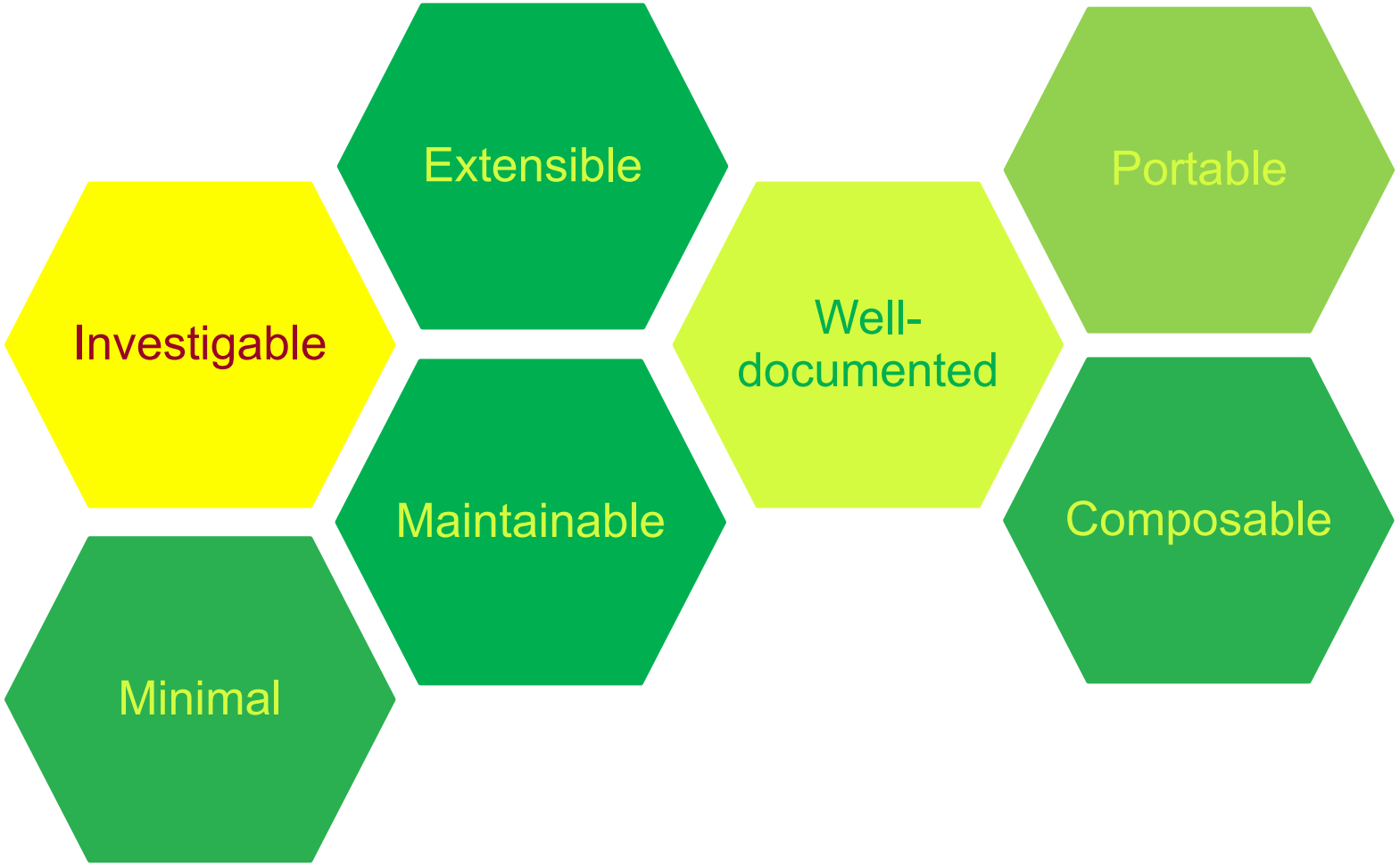

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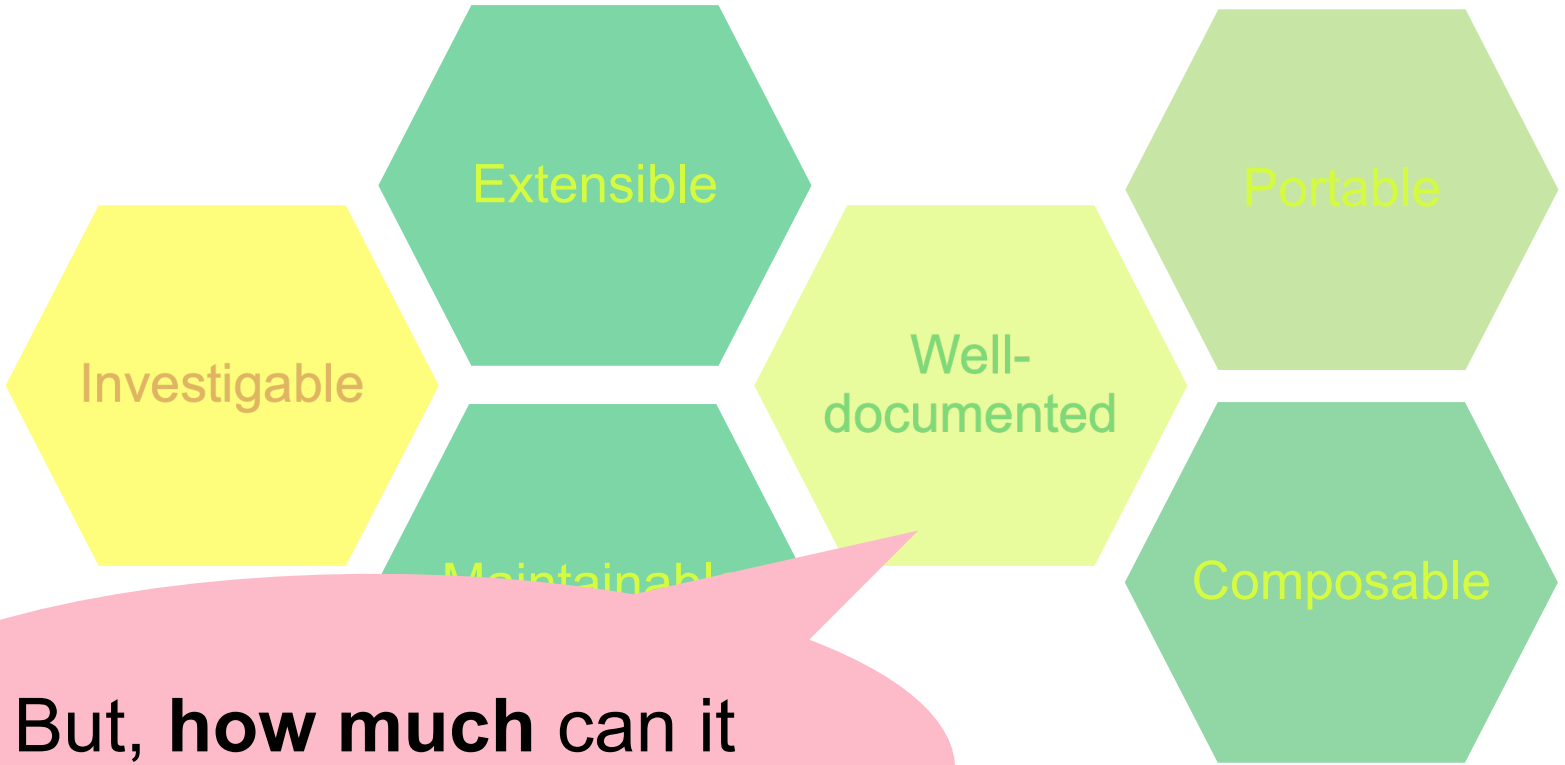
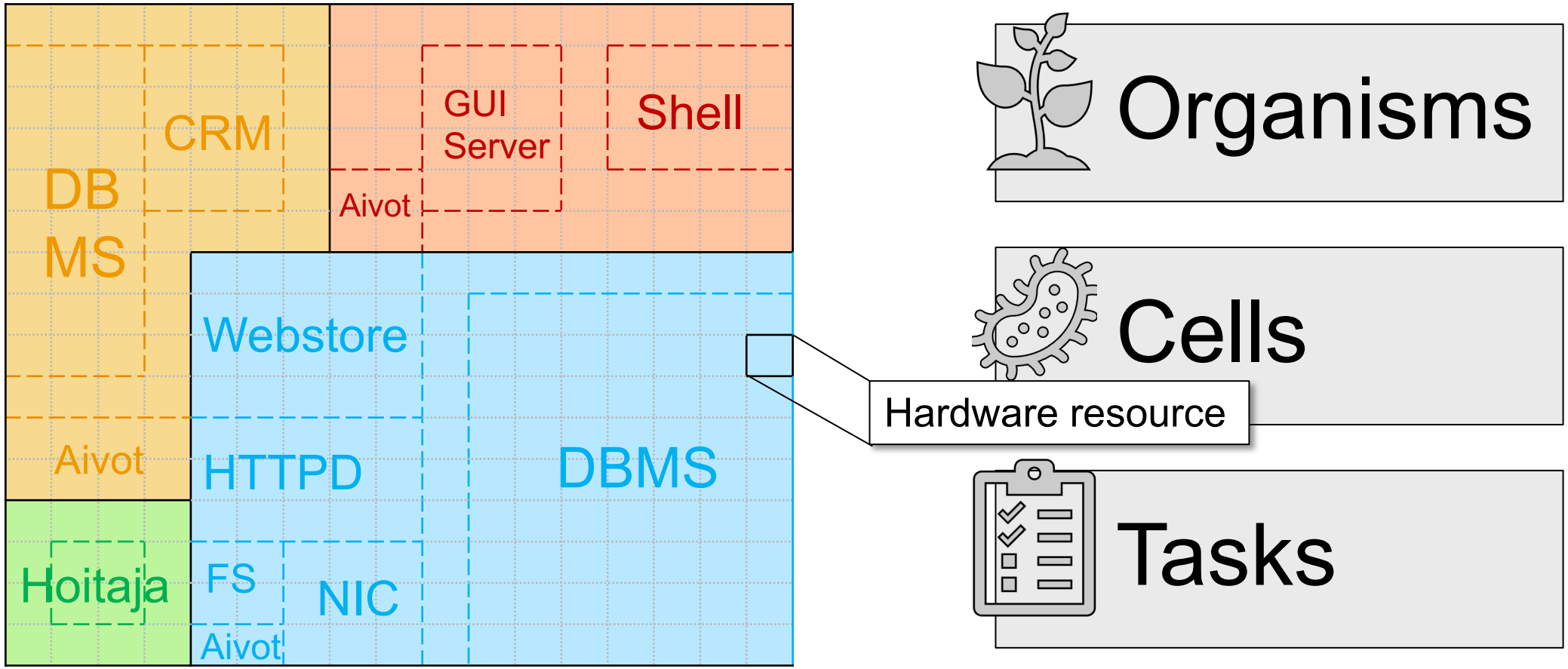


Meet

EalánOS

… an experimental implementation of the MxKernel architecture using the Genode OS Framework

EalánOS — Concepts



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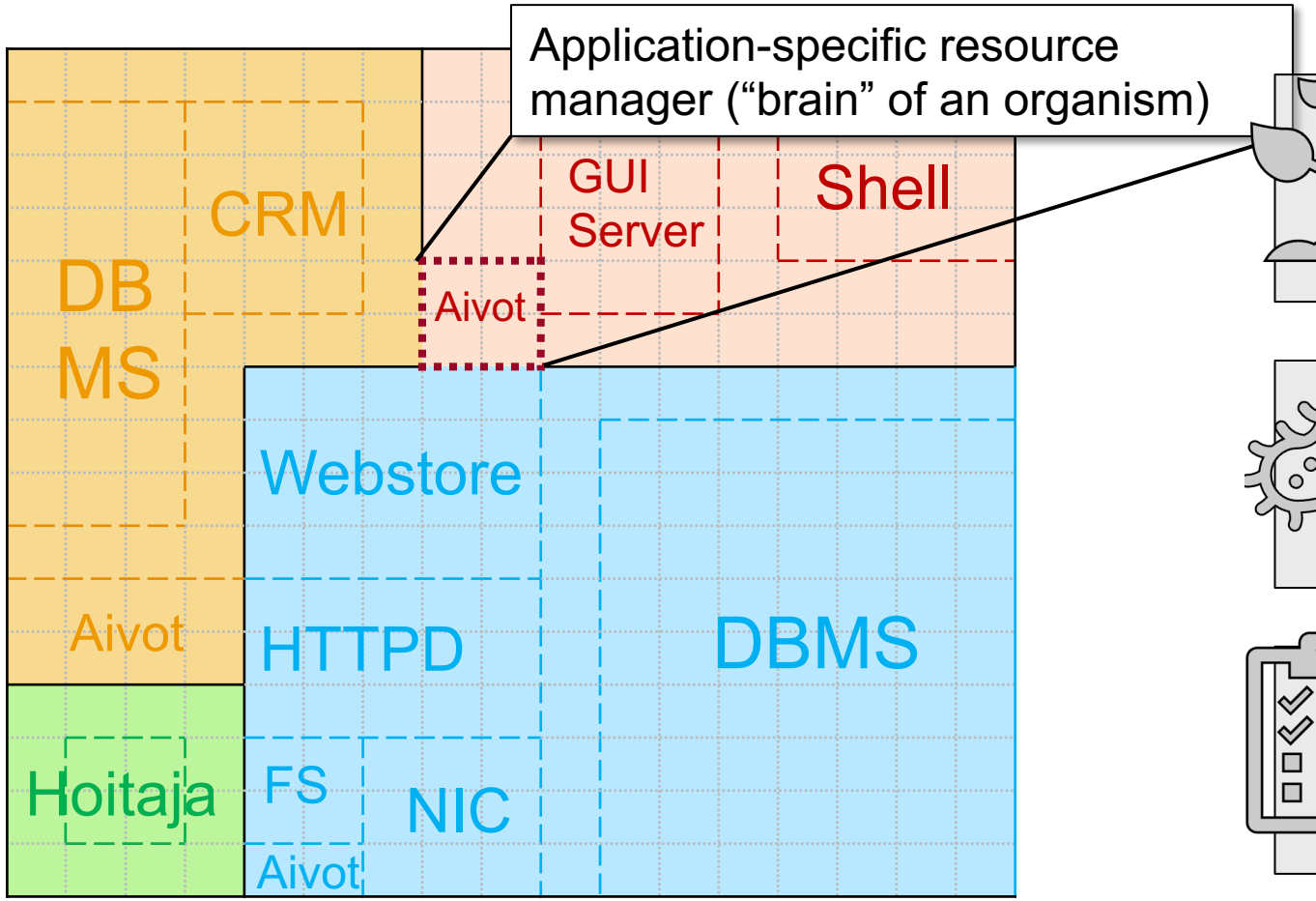


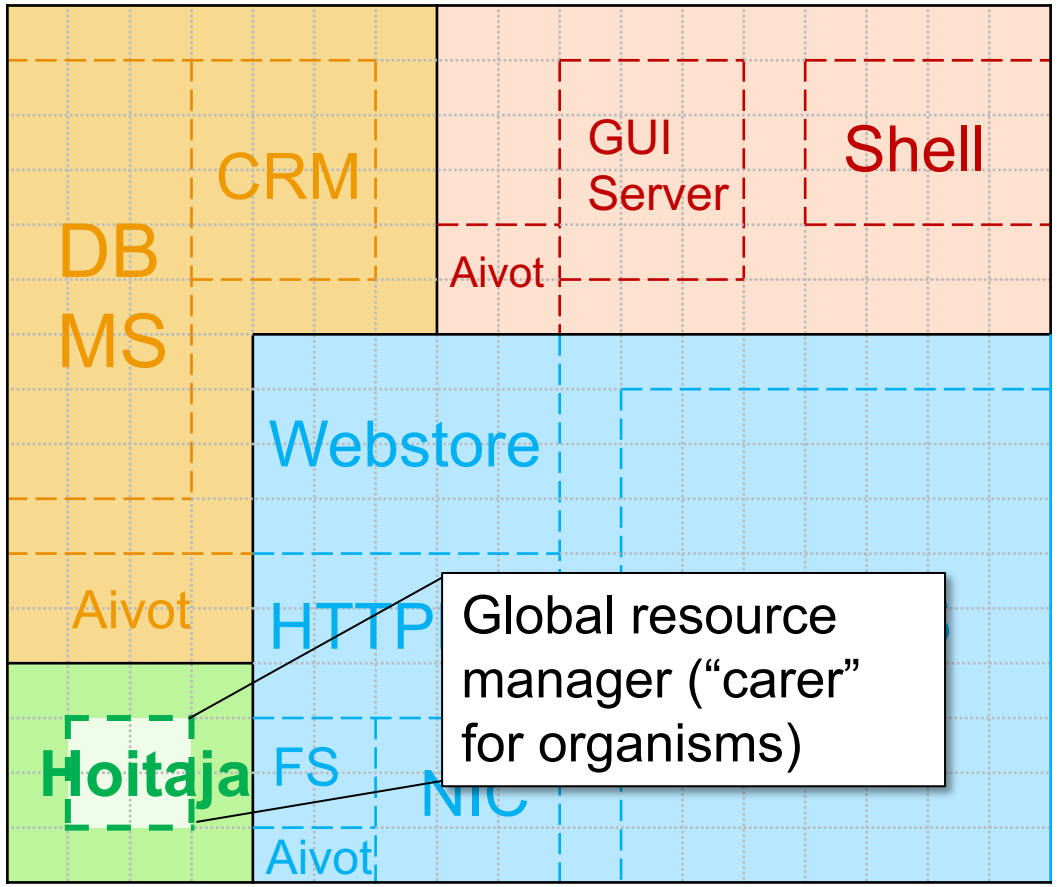
Organisms

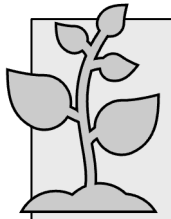
- Resource container for a **user-session**
- **Custom** OS services

Cells

Tasks

EalánOS — Concepts





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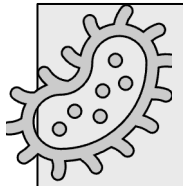
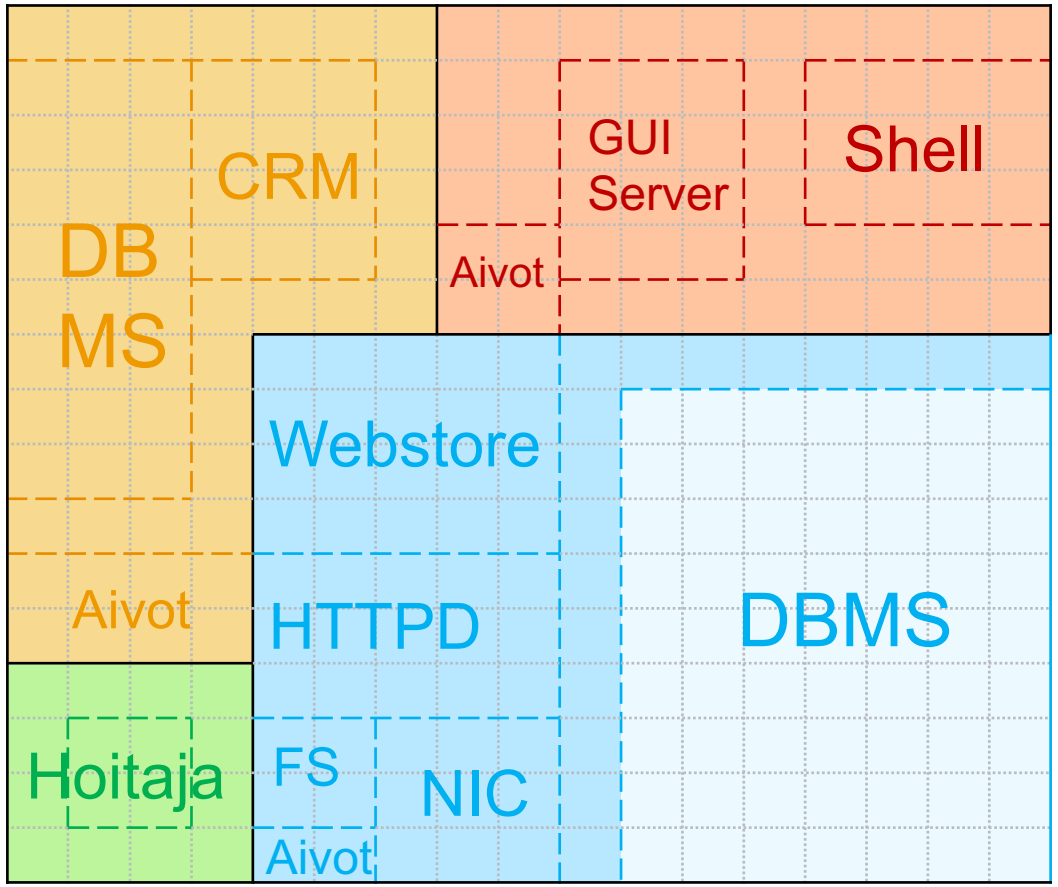
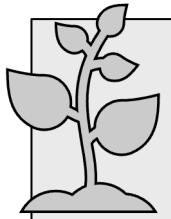


Cells

Tasks

EalánOS — Concepts





Organisms

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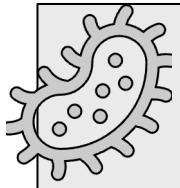
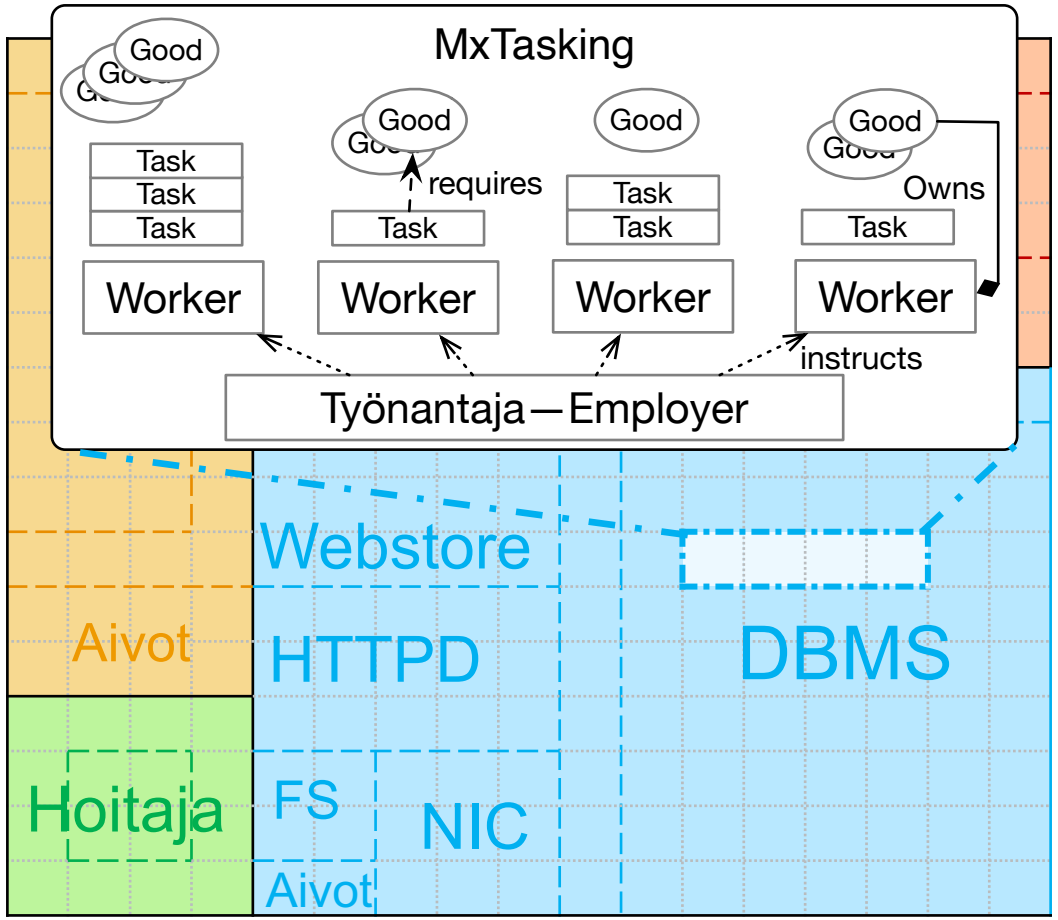


Cells

- ***Elastic*** resource container
- Contains a **single** process

Tasks

EalánOS — Concepts



Organisms

- Resource container for a **user-session**
- **Custom** OS services

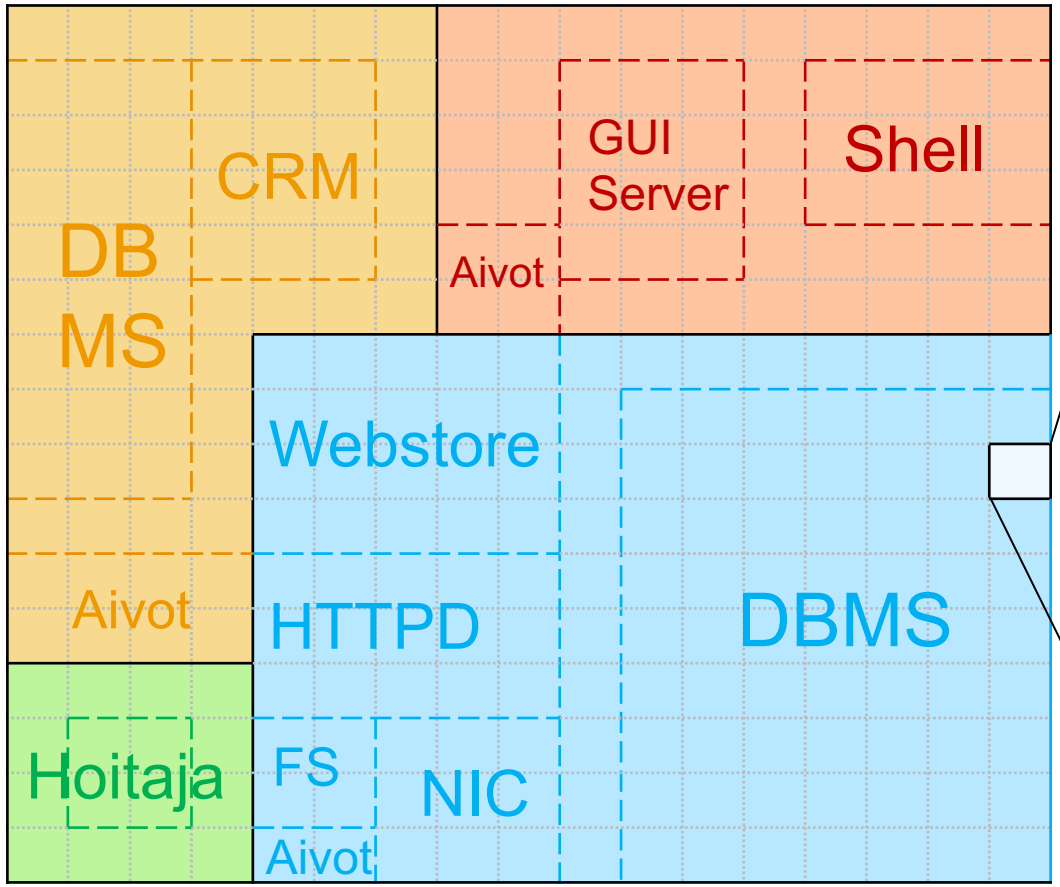
Cells

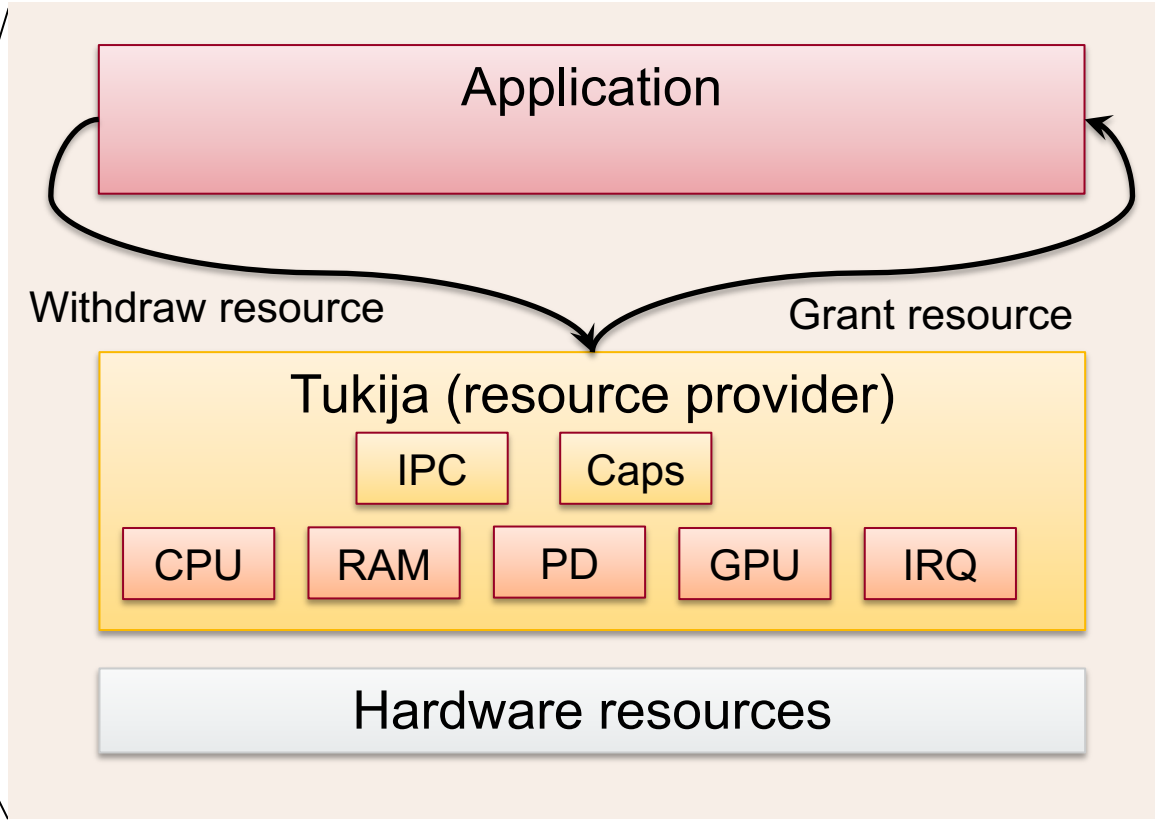
- ***Elastic*** resource container
- Contains a **single** process

Tasks

- closed units of work
- **not** preemptable

EalánOS — Architecture

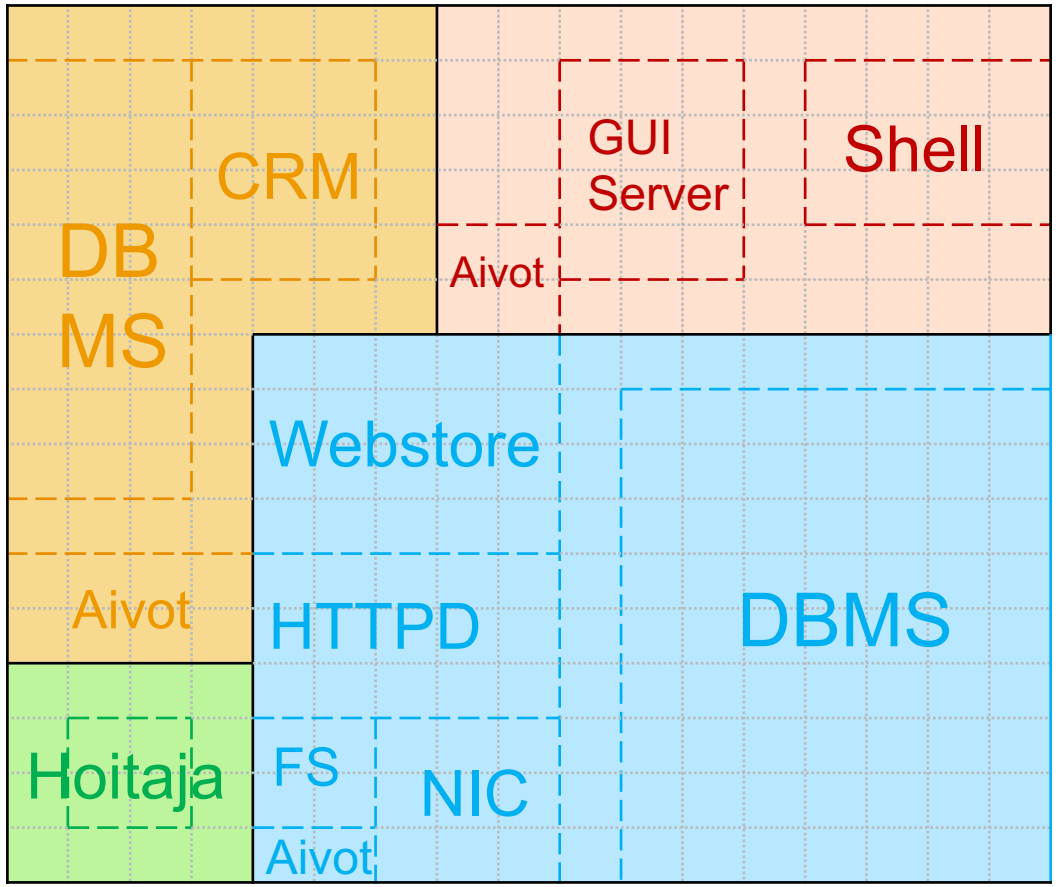


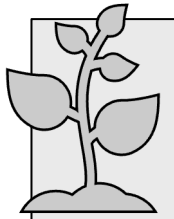


How Genode assists in creating a research OS

THE MAKING-OF EALÀNOS

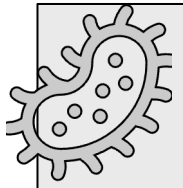
EalánOS — What do we need? What do we have?





Organisms

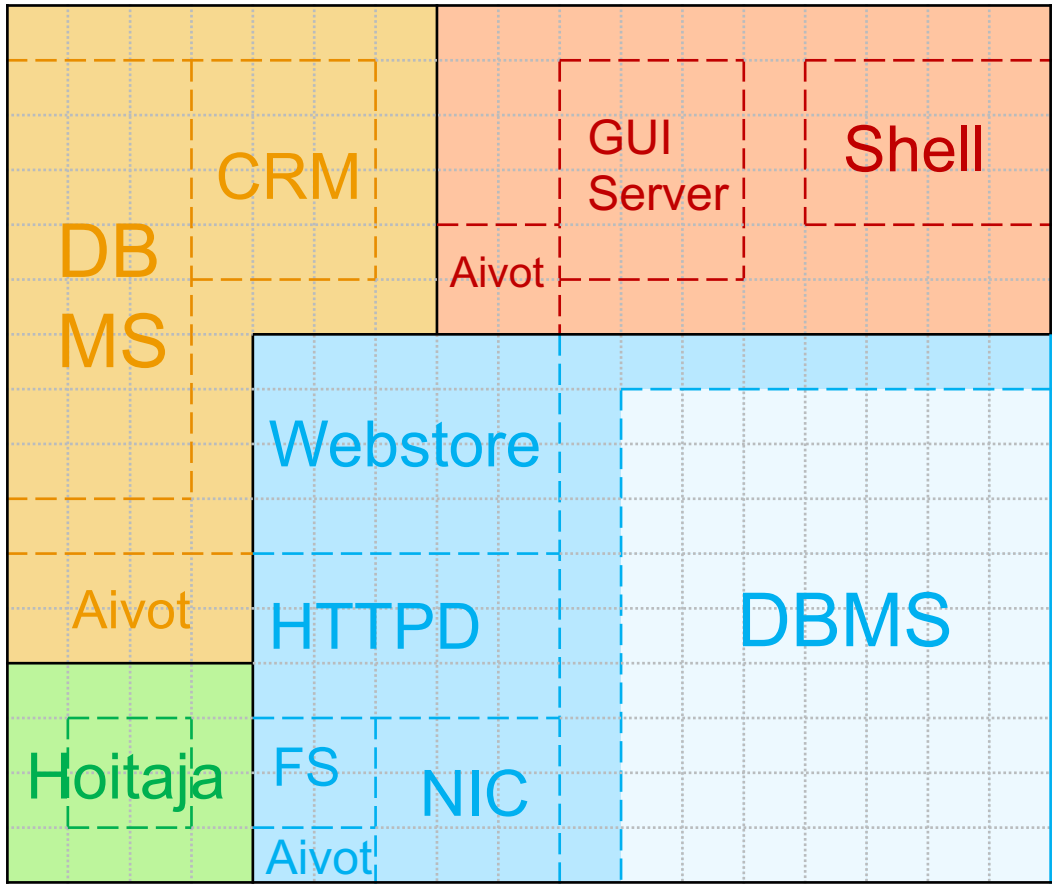
- **Service interception**

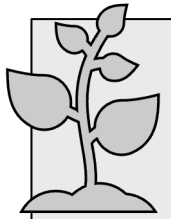


Cells

Tasks

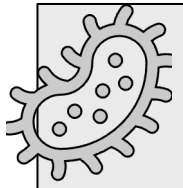
EalánOS — What do we need? What do we have?





Organisms

- Service interception

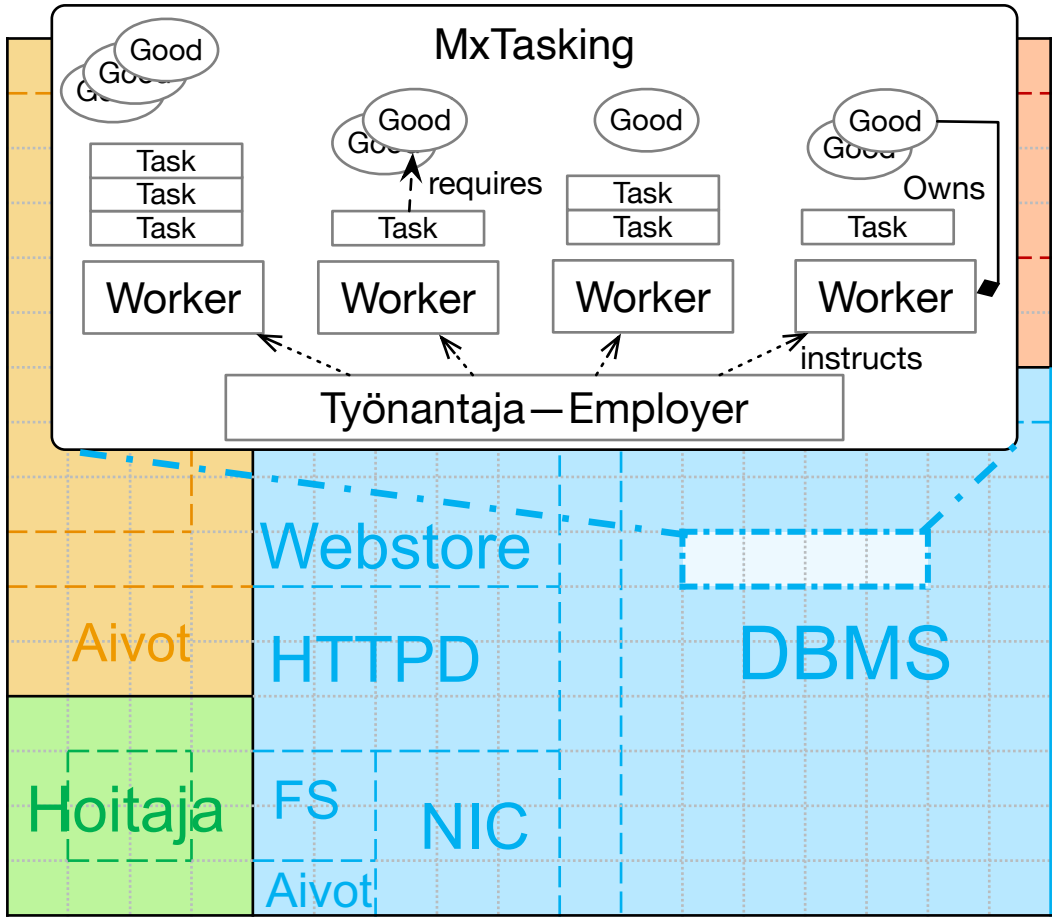


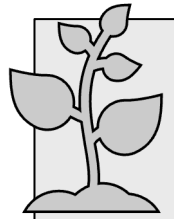
Cells

- **Genode components**

Tasks

EalánOS — What do we need? What do we have?





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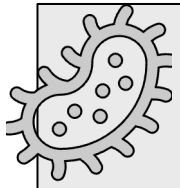


Cells

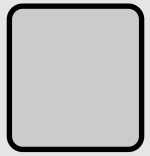
- Genode components

Tasks

- **Port MxTasking[1]**

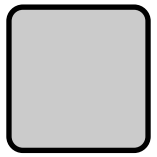
[1] MxTasking: Task-based framework with built-in prefetching and synchronization — github.com/jmuehlig/mxtasking

MxTasking — What does it need?



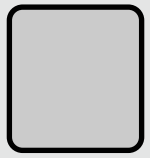
Standard C++ library

- For internal data structures
- Portability



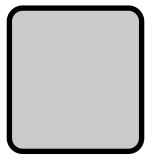
Filesystem

- For benchmarks
- For writing profiling results



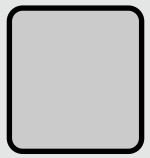
Timer support

- For garbage collection
- And profiling



Multicore support

- Needed for task parallelism



NUMA support

- For NUMA-aware task scheduling
- And data placement

MxTasking — What does it need?

Standard C++ library

- For internal data structures
- Portability

Filesystem

- For benchmarks
- For writing profiling results

Timer support

- For garbage collection
- And profiling

Multicore support

- Needed for task parallelism

NUMA support

- For NUMA-aware task scheduling
- And data placement

Filling the gaps … NUMA support for Genode

NOVA extension for NUMA

- for accessing SRAT entries

Topology service

- for querying topology from user-space

Regional heaps

- for NUMA-aware memory allocation

MxTasking glue-code

Filling the gaps … NUMA support for Genode

NOVA extension for NUMA

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365 LoC

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365 LoC

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683 LoC

MxTasking glue-code

Filling the gaps … NUMA support for Genode

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365 LoC

Topology service
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531 LoC

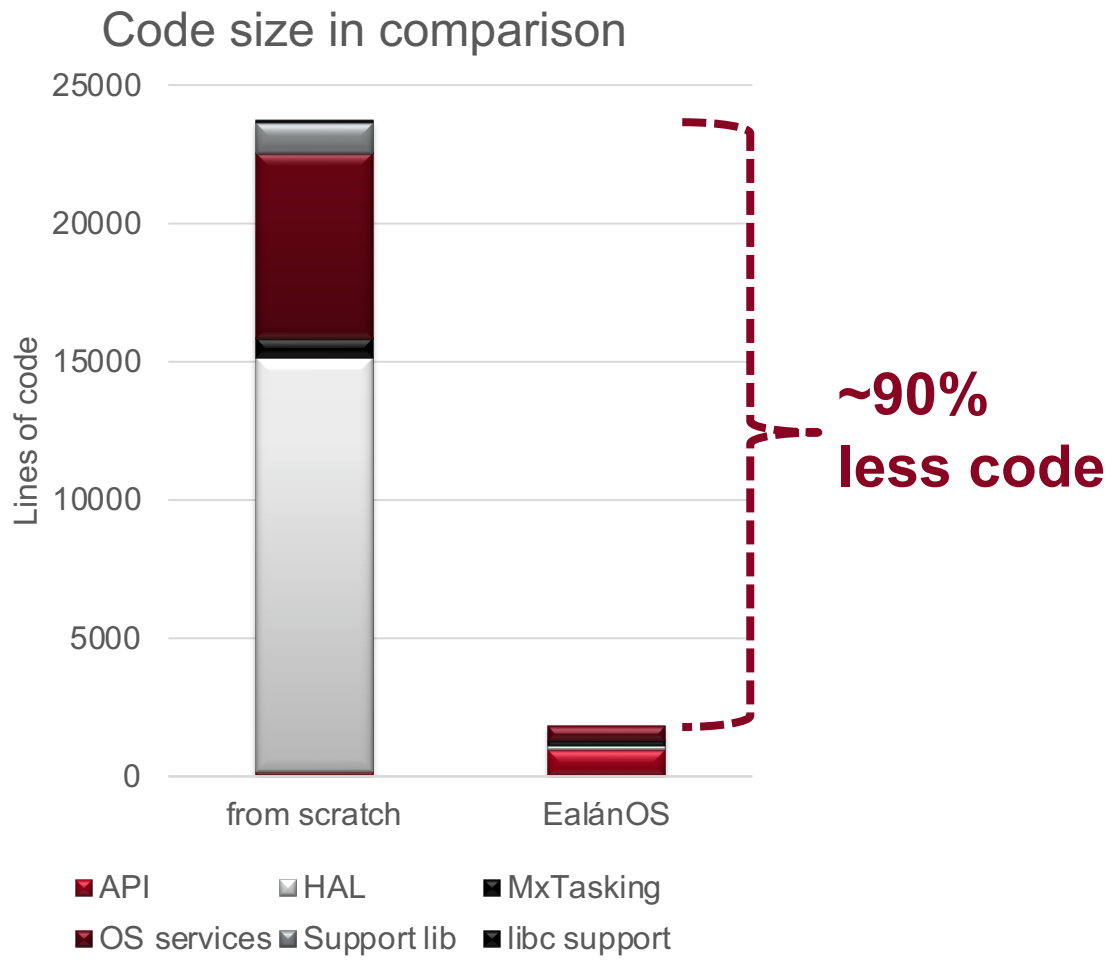
Regional heaps
- for NUMA-aware memory allocation

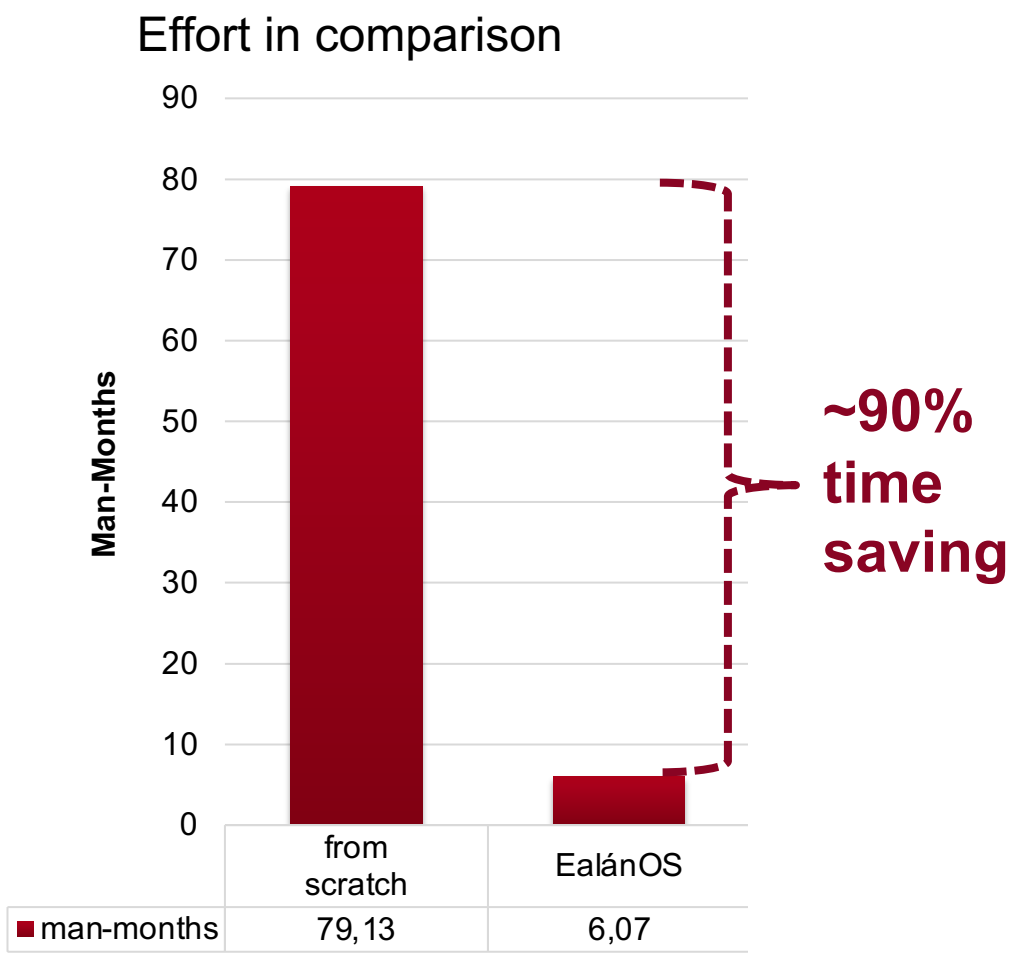
683 LoC

MxTasking glue-code

186 LoC

What you can win with Genode





Automated Experiments with Genode

TO THE LAB!

Sculpting a Genode system

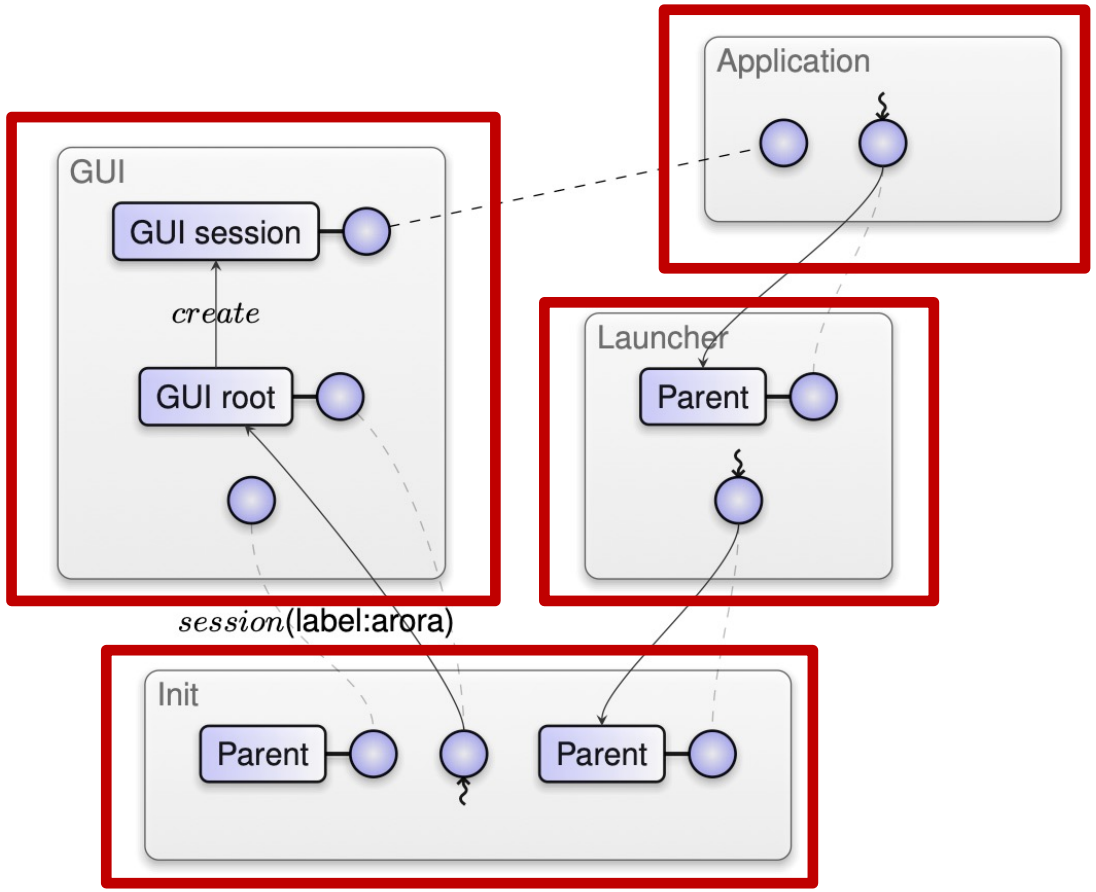


Figure 11: Session creation at the server.

- A **Genode** system **consists** of **components**

*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Sculpting a Genode system

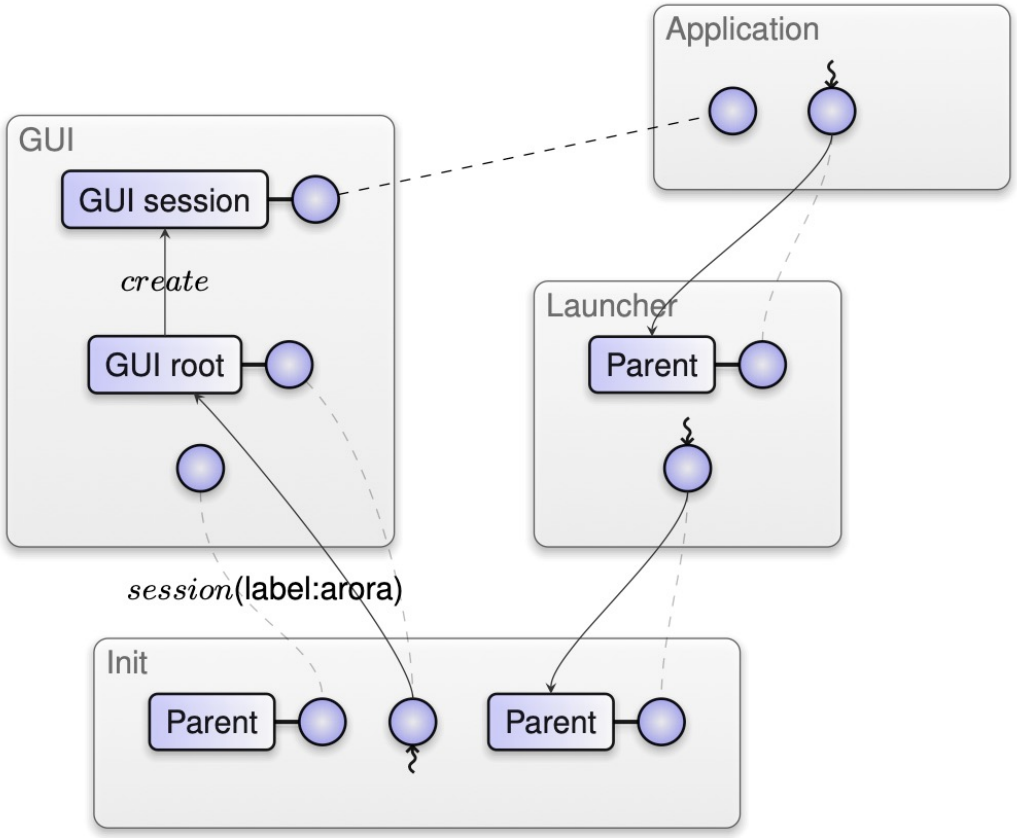


Figure 11: Session creation at the server.

- A **Genode** system **consists** of **components**
- Components are **applications**, OS **servers**, **drivers** etc.

*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Sculpting a Genode system

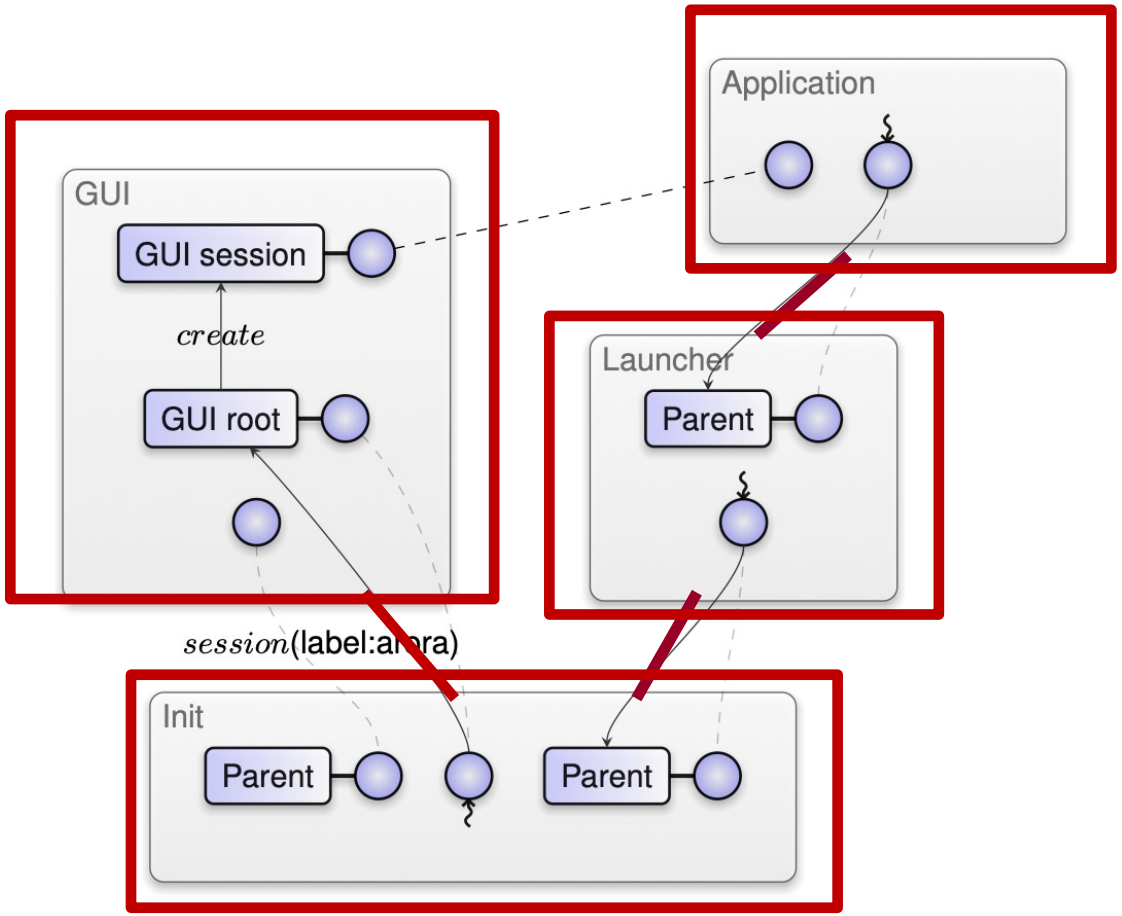


Figure 11: Session creation at the server.

- A **Genode** system **consists** of **components**
- Components are **applications**, OS **servers**, **drivers** etc.
- Running system is a **tree of components**

*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Sculpting a Genode system

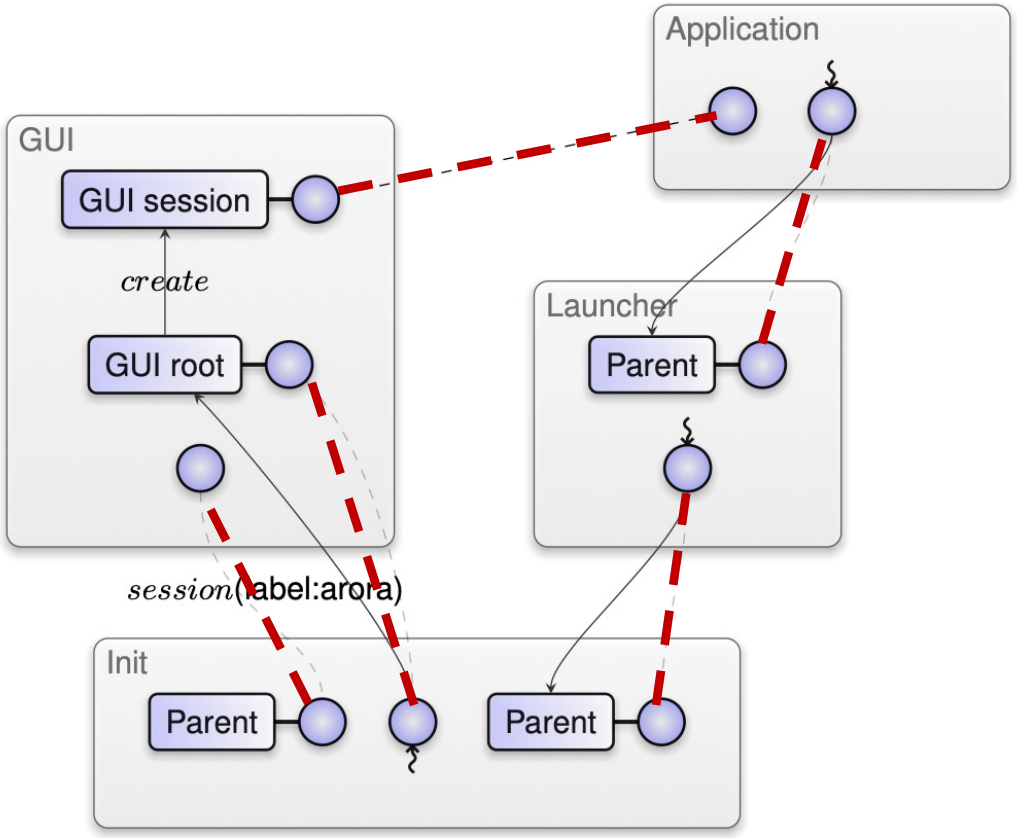


Figure 11: Session creation at the server.

- A **Genode** system **consists** of **components**
- Components are **applications**, OS **servers**, **drivers** etc.
- Running system is a **tree of components**
- **Scenarios specify** the **tree of components** and the relation among its nodes **as XML** configurations

*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Sculpting a Genode system

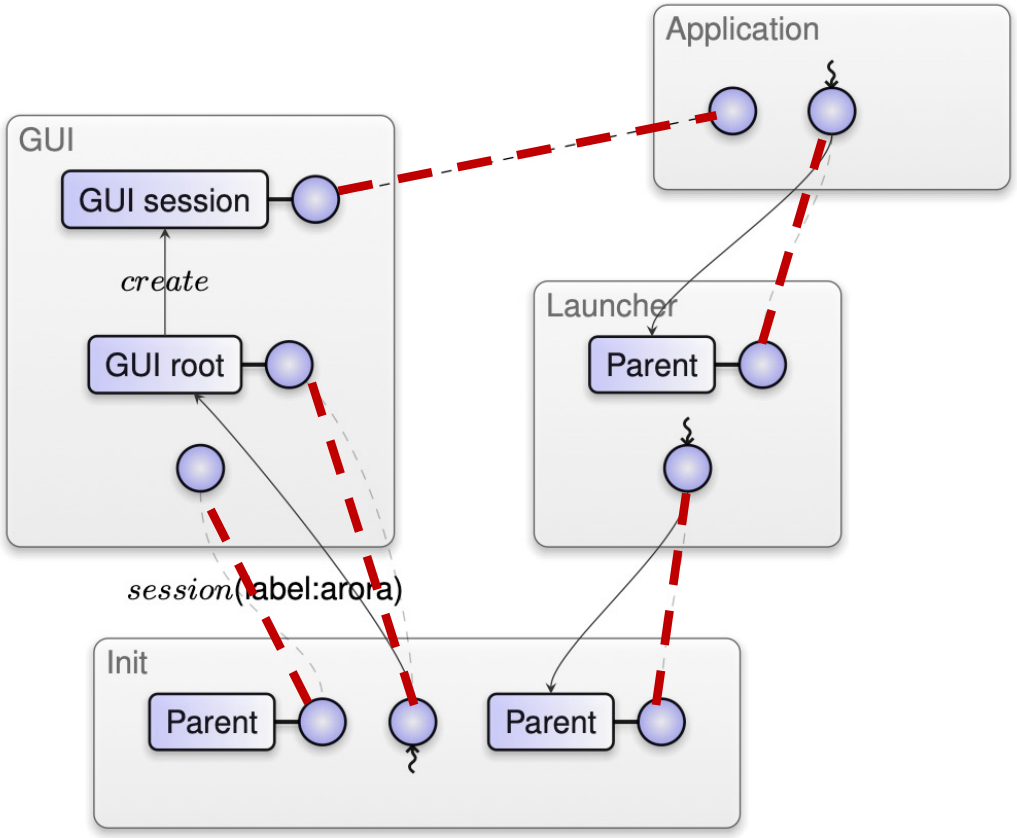


Figure 11: Session creation at the server.

Now, let's try an example experiment!

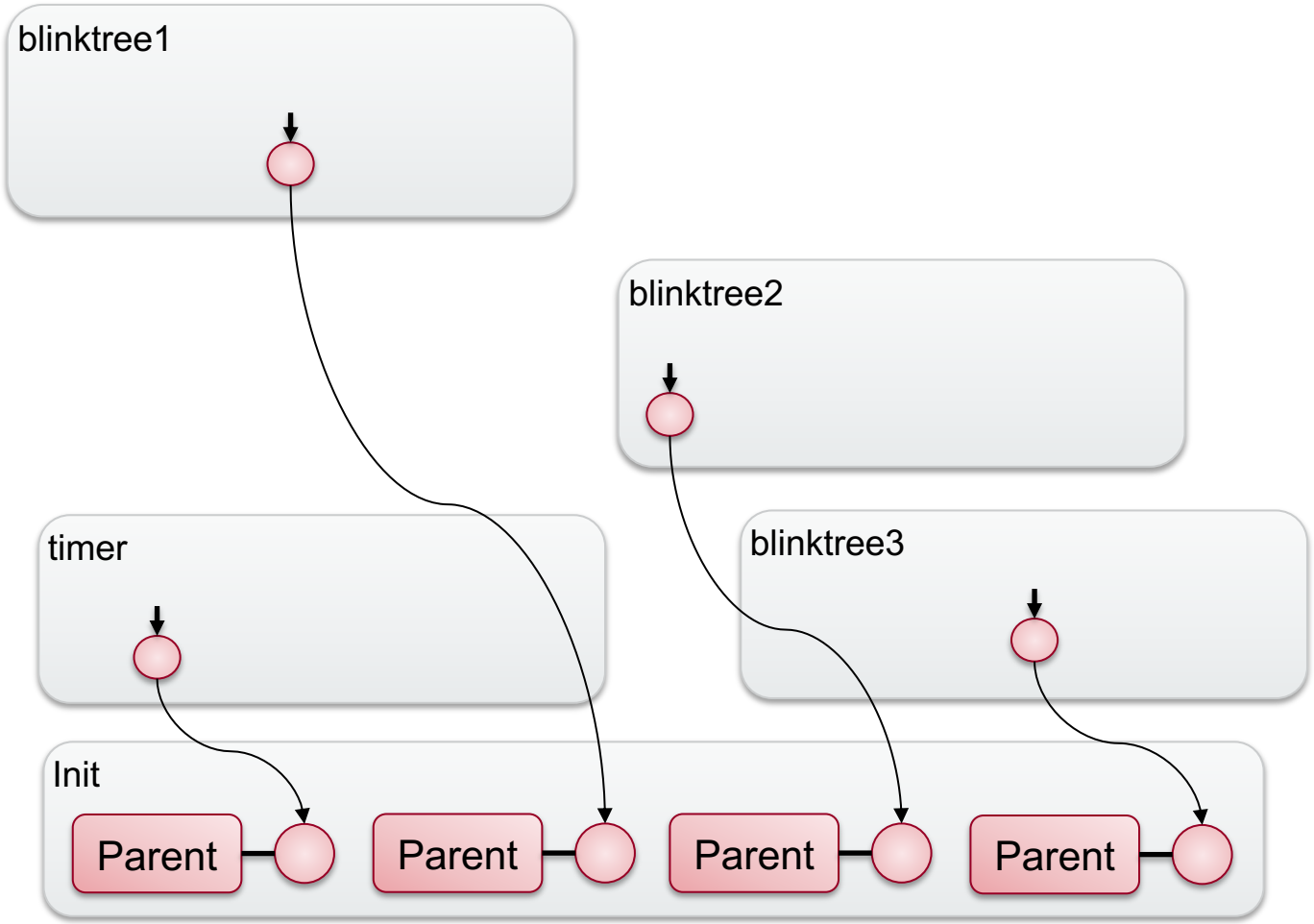
*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Example: B-link tree benchmark

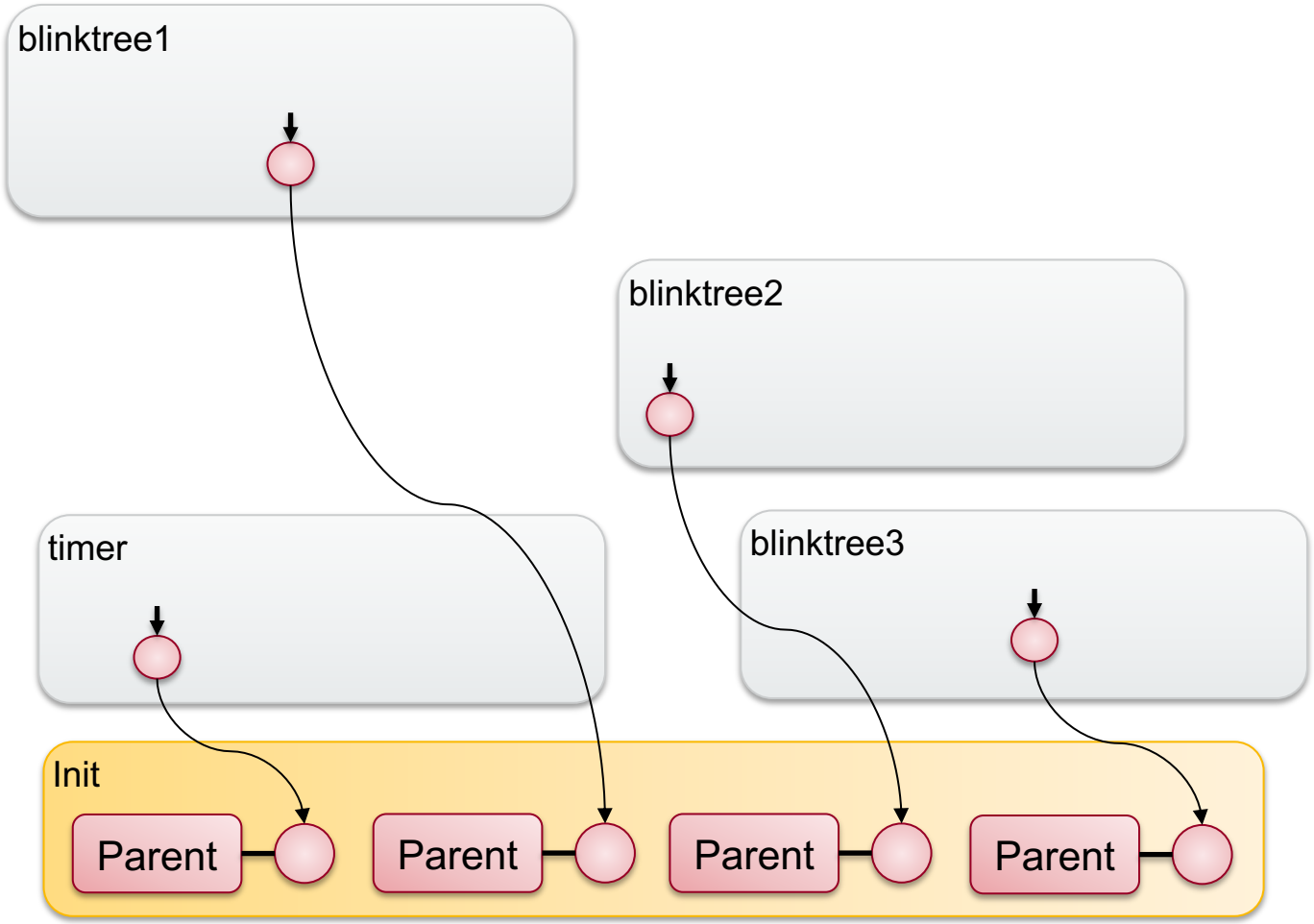
- Investigate how **throughput** of benchmark is **affected** when we run **multiple instances**
  - On the **same** set of CPU cores
  - On a **disjunct** set of CPU cores
- **Which** scenario will yield the **higher** throughput at the respective **maximum** of cores?

- B-link trees are a wide-spread **datastructure** for **indexing** in **database** systems.
- The B-link tree benchmark is based on **YCSB**, a **common benchmark** for **key-value stores**.

Example: B-link tree benchmark

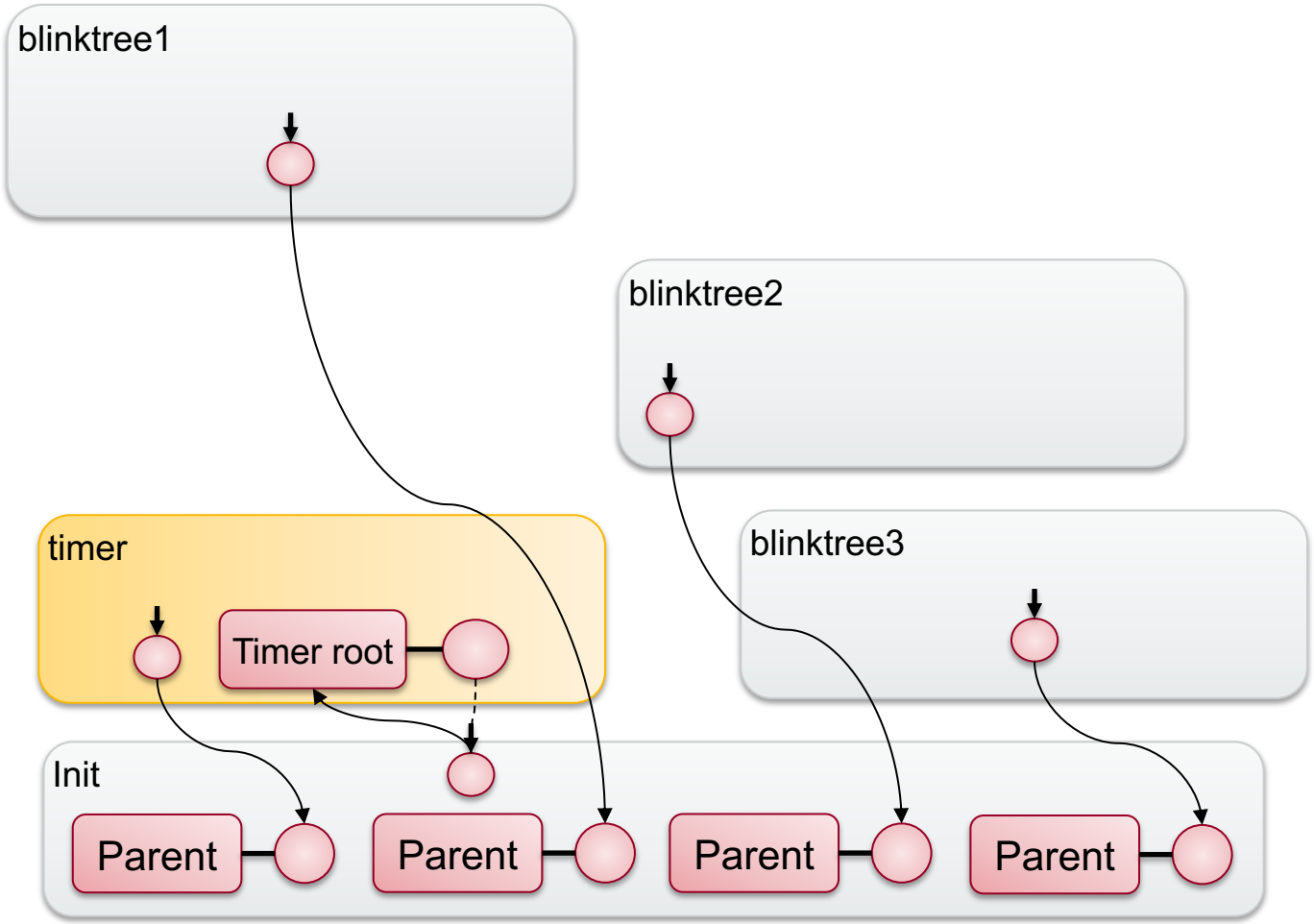


Example: B-link tree benchmark



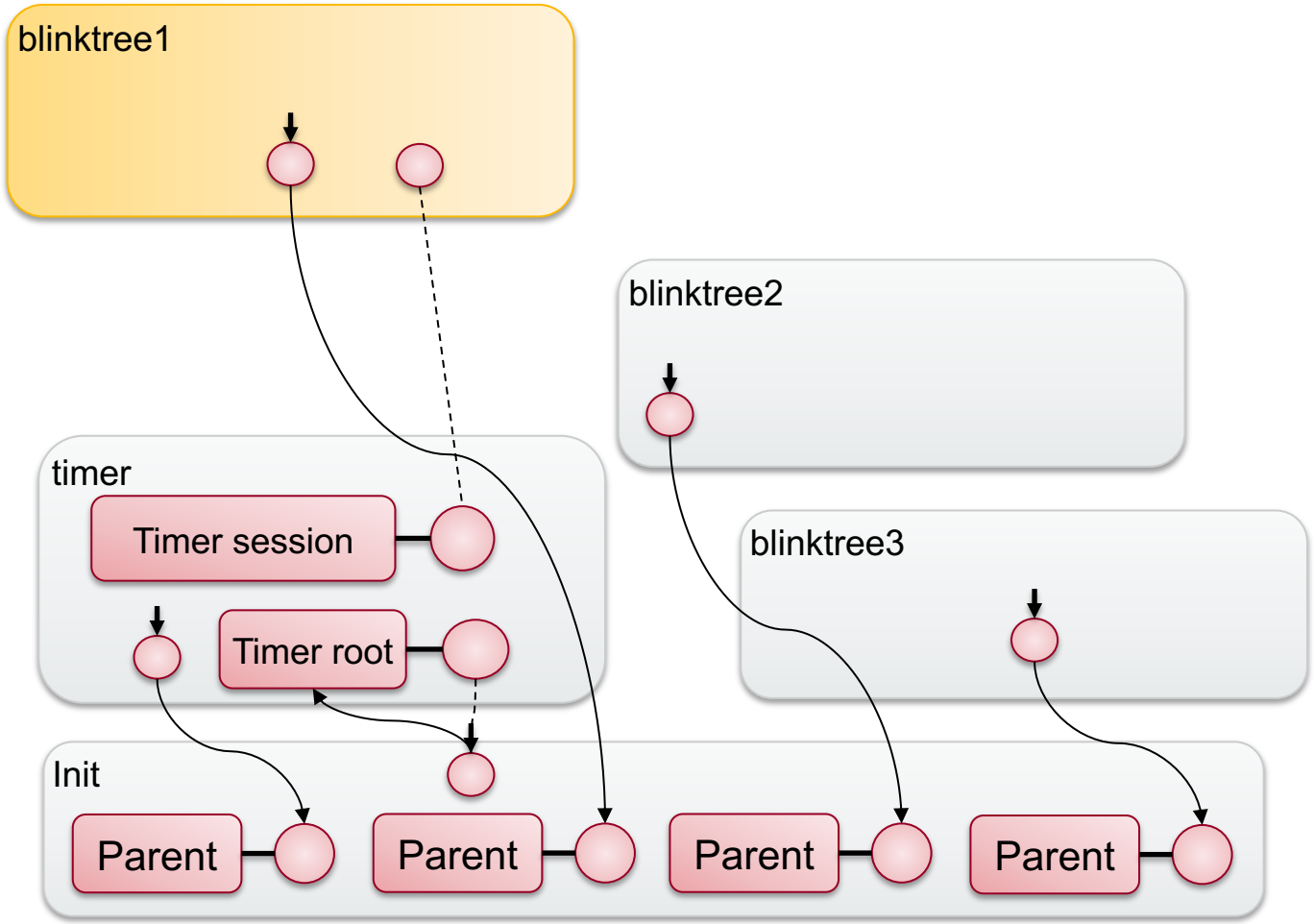

```
<config>
    <start name="timer">
    </start>
    <start name="blinktree1">
        <binary name="blinktree"/>
    </start>
    <start name="blinktree2">
        <binary name="blinktree"/>
    </start>
    <start name="blinktree3">
        <binary name="blinktree"/>
    </start>
</config>
```

Example: B-link tree benchmark




```
<config>
   <start name="timer">
      <provides><service
name="Timer"/></provides>
      <route>
                  <any-
service><parent/><any-child/></any-
service>
            </route>
   </start>
   <start name="blinktree1">
      <binary name="blinktree"/>
   </start>
   <start name="blinktree2">
      <binary name="blinktree"/>
   </start>
   <start name="blinktree3">
      <binary name="blinktree"/>
   </start>
</config>
```

Example: B-link tree benchmark




```
<config>
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          <provides><service name="Timer"/></provides>
      <route>
             <any-service><parent/><any-child/></any-
service>
         </route>
   </start>
    <start name="blinktree1">
        <binary name="blinktree"/>
        <route>
            <service name="Timer"><child
name="timer"/></service>
            <any-service><parent/><any-
child/></any-service>
        </route>
    </start>
   <start name="blinktree2">
      <binary name="blinktree"/>
   </start>
   <start name="blinktree3">
      <binary name="blinktree"/>
   </start>
</config>
```

Example: B-link tree benchmark

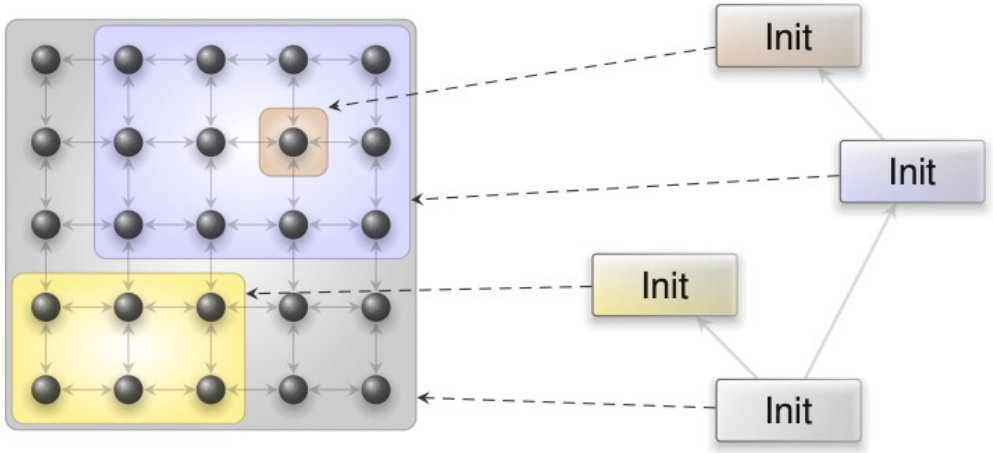
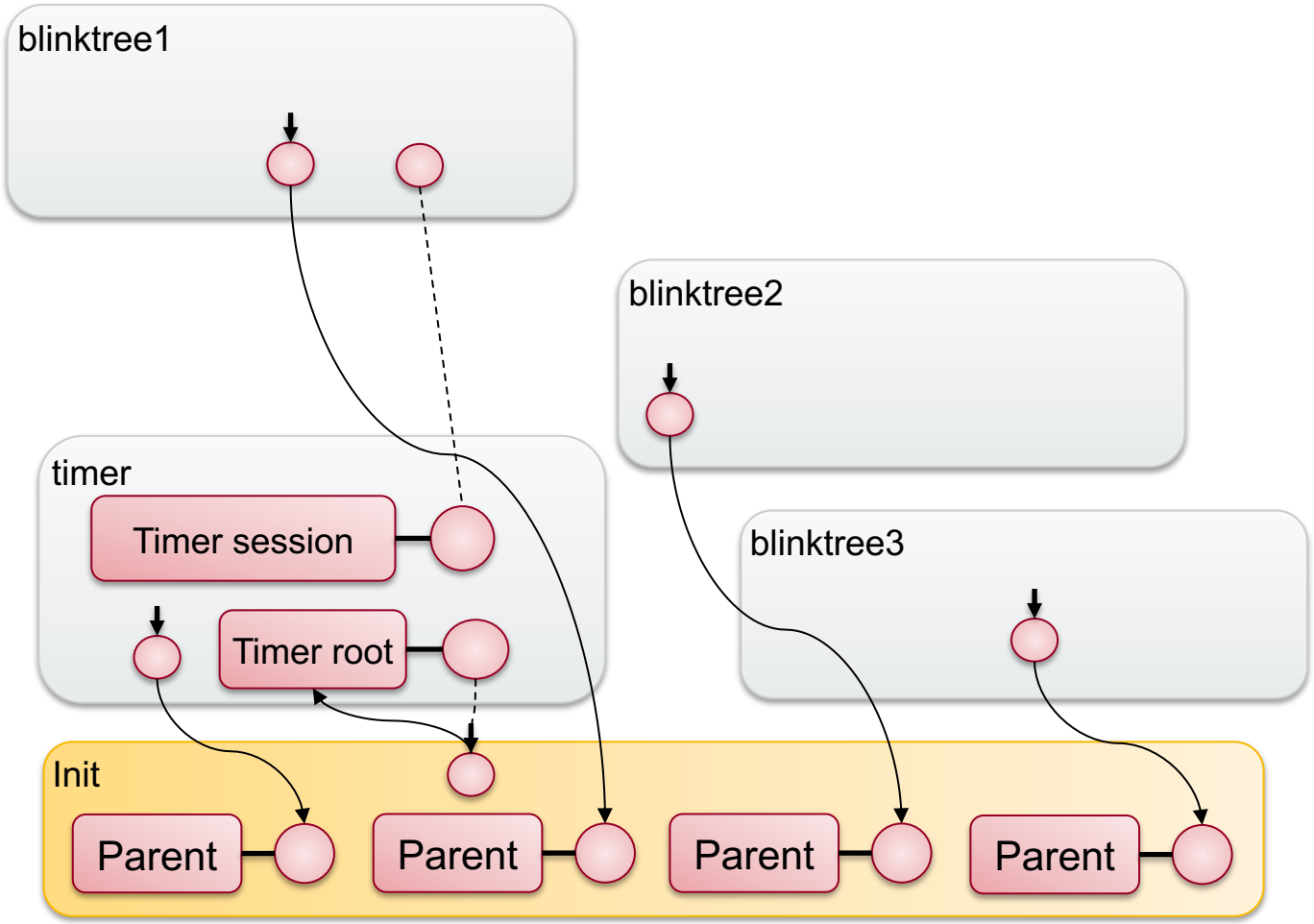


Figure 48: Successive virtualization of CPU affinity spaces by nested instances of init

- Affinity spaces **map components** to a set of **CPU cores**
- And they can be **nested**

*Source: "**Genode Foundations 22.05**" -- Norman Feske, Genode Labs GmbH, Dresden, 2022*

Example: B-link tree benchmark

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  <start name=“timer”>
        <provides><service name=“Timer”/></provides>
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    </route>
  </start>
  <start name=“blinktree1”>
    <binary name=“blinktree”/>
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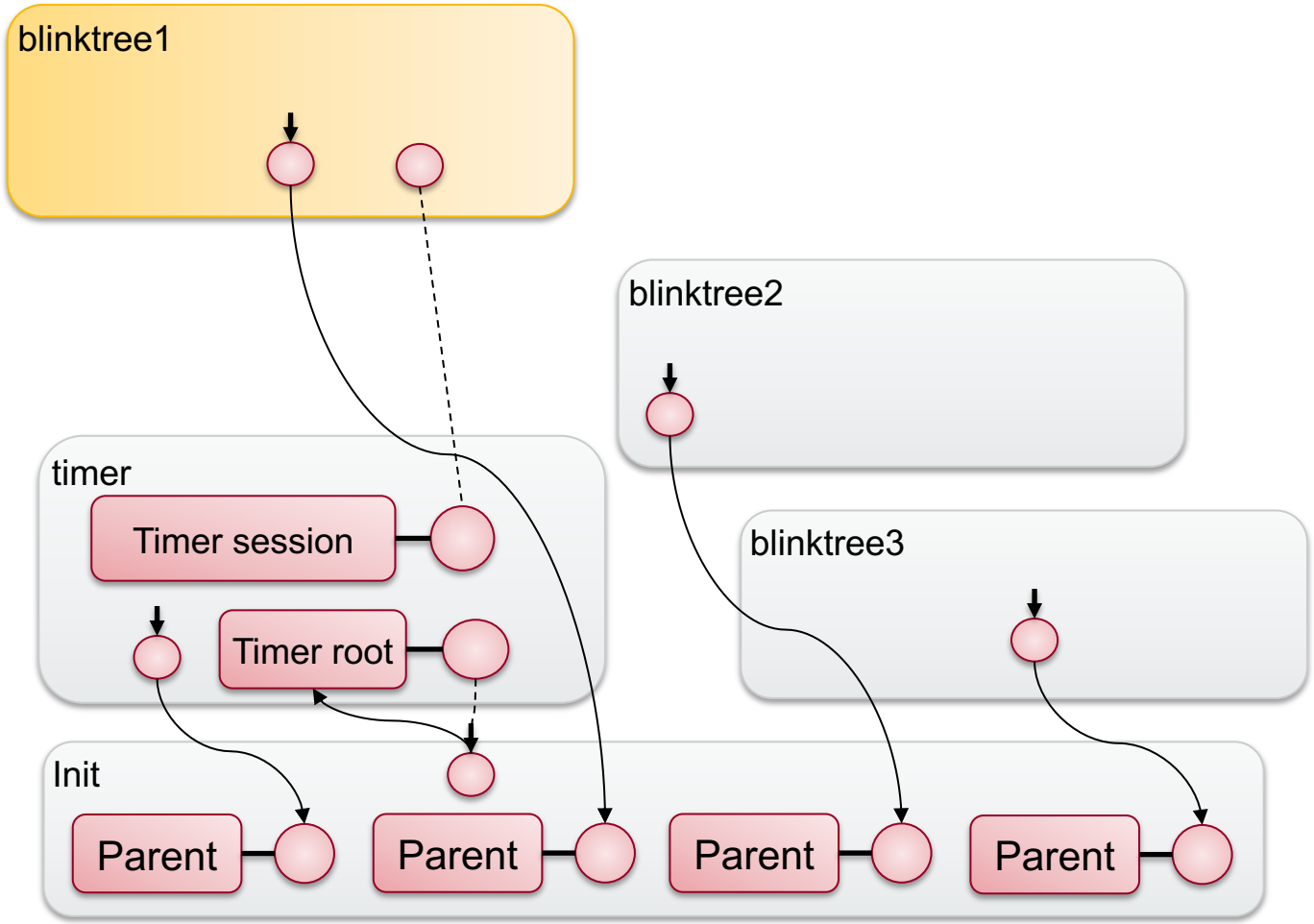
      <service name="Timer"><child name="timer"/></service>
      <any-service><parent/><any-child/></any-service>
    </route>
  </start>
  <start name=“blinktree2”>
    <binary name=“blinktree”/>
  </start>
  <start name=“blinktree3”>
    <binary name=“blinktree”/>
  </start>
</config>
```

Example: B-link tree benchmark




```
<config>
   <affinity-space width=”64” height="1"/>
   <start name=“timer”>
          <provides><service name=“Timer”/></provides>
       <route>
             <any-service><parent/><any-child/></any-
service>
          </route>
   </start>
   <start name=“blinktree1”>
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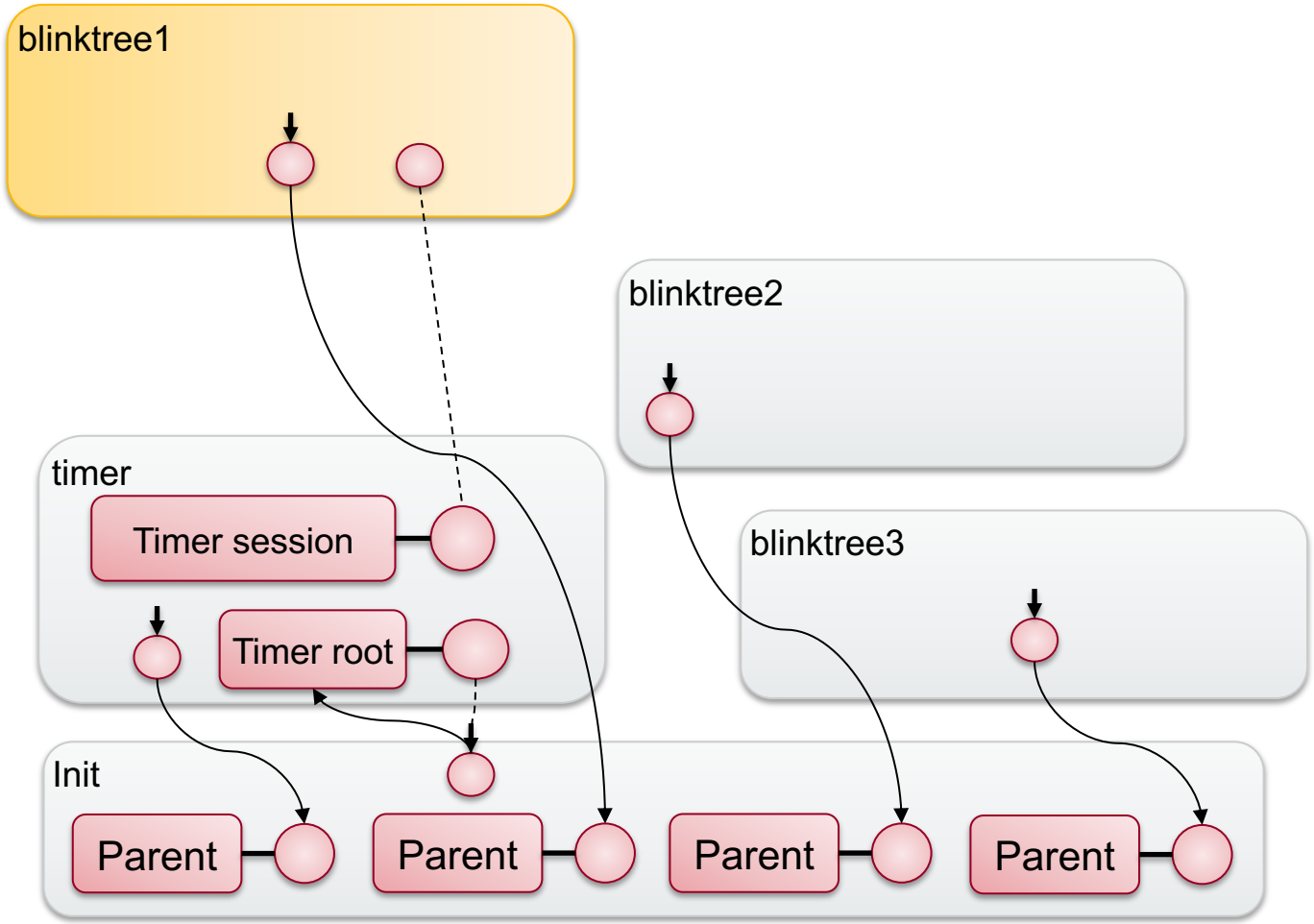
width=”63" height="1"/>
       <binary name=“blinktree”/>
       <route>
          <service name="Timer"><child
name="timer"/></service>
          <any-service><parent/><any-child/></any-
service>
       </route>
   </start>
   <start name=“blinktree2”>
       <binary name=“blinktree”/>
   </start>
   <start name=“blinktree3”>
       <binary name=“blinktree”/>
   </start>
</config>
```

Example: B-link tree benchmark




```
<config>
   <affinity-space width=”64” height="1"/>
   <start name=“timer”>
          <provides><service name=“Timer”/></provides>
       <route>
             <any-service><parent/><any-child/></any-
service>
          </route>
   </start>
   <start name=“blinktree1”>
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height="1"/>
          <resource name=”RAM”
quantum=“80G”/>
       <binary name=“blinktree”/>
       <route>
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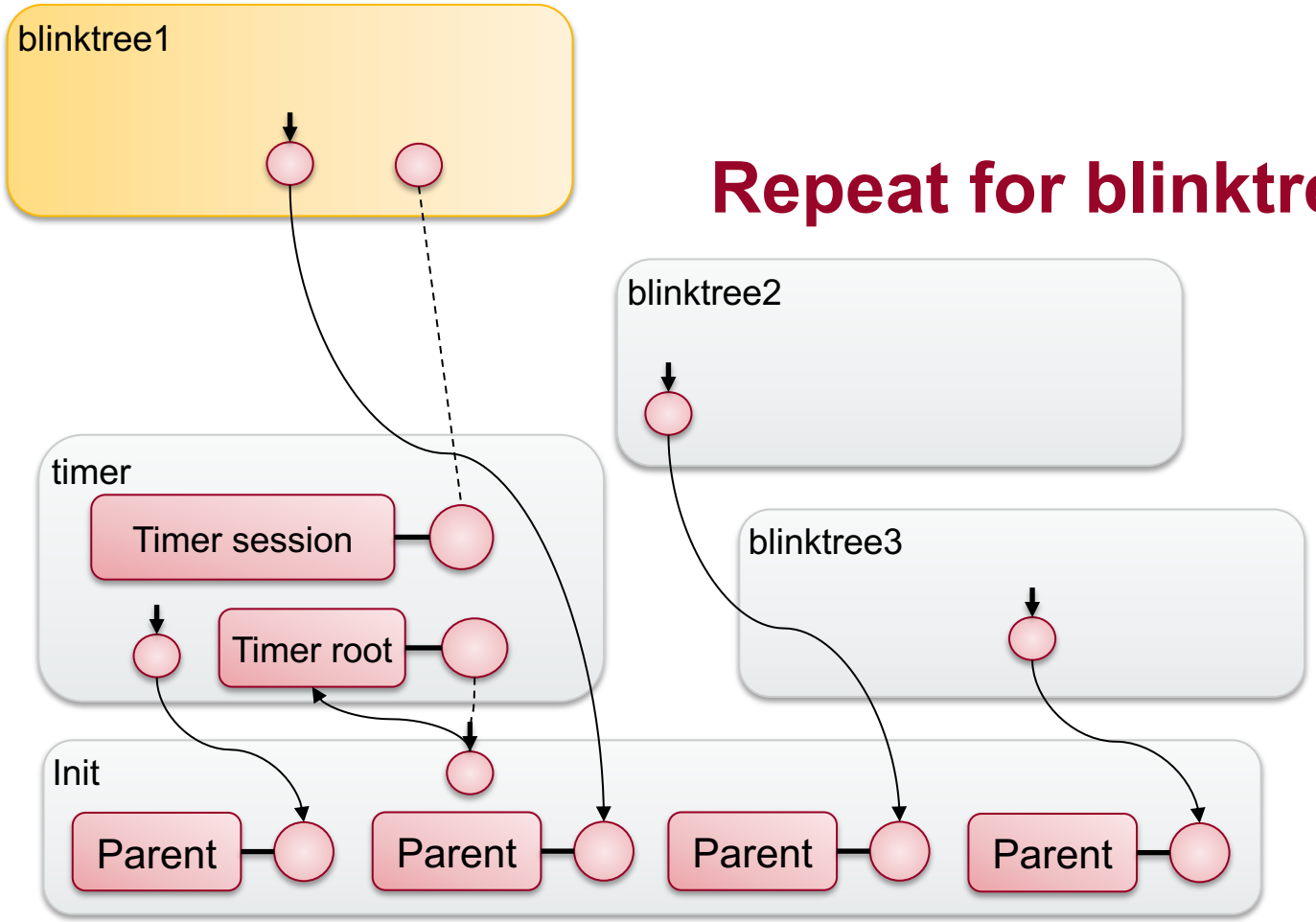
name="timer"/></service>
          <any-service><parent/><any-child/></any-
service>
       </route>
   </start>
   <start name=“blinktree2”>
       <binary name=“blinktree”/>
   </start>
   <start name=“blinktree3”>
       <binary name=“blinktree”/>
   </start>
</config>
```

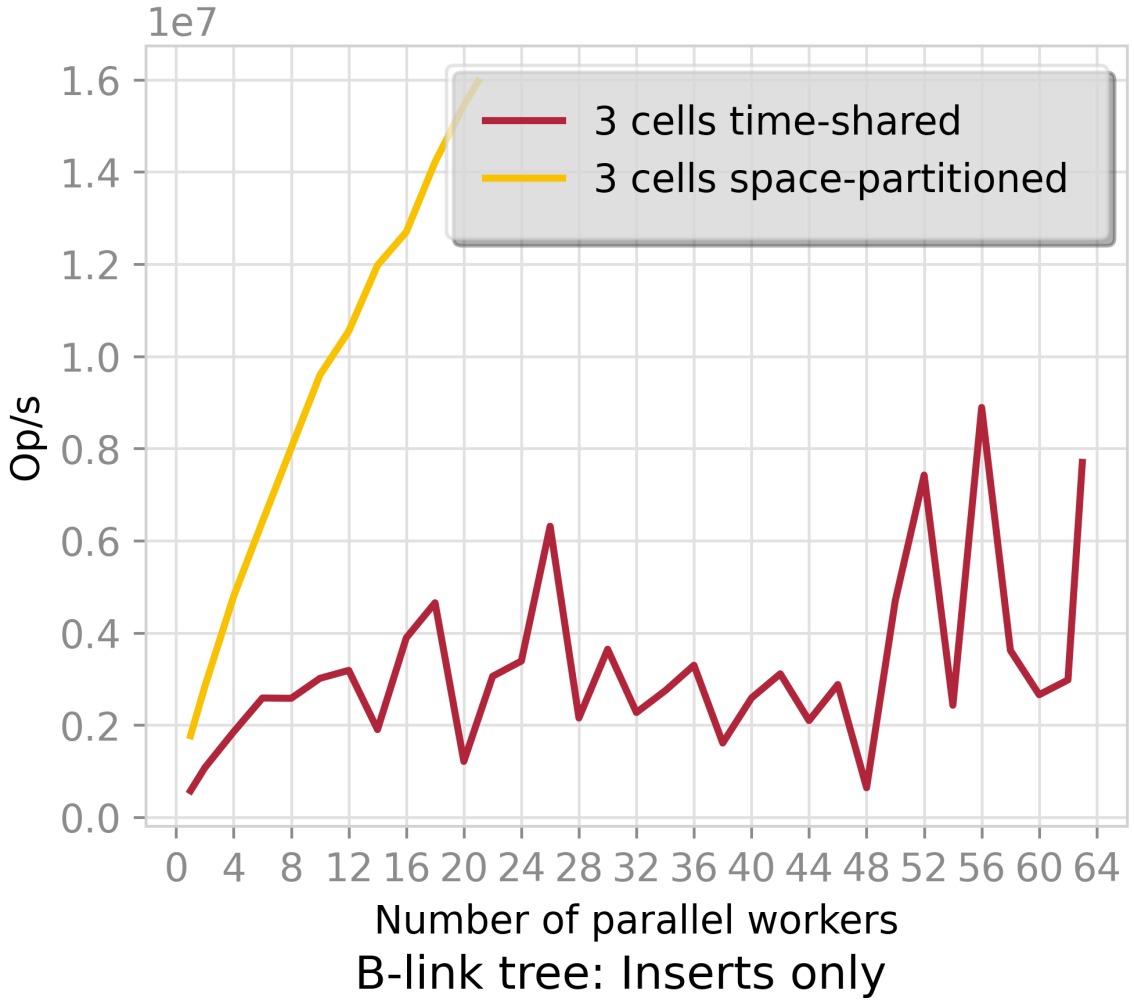
Example: B-link tree benchmark



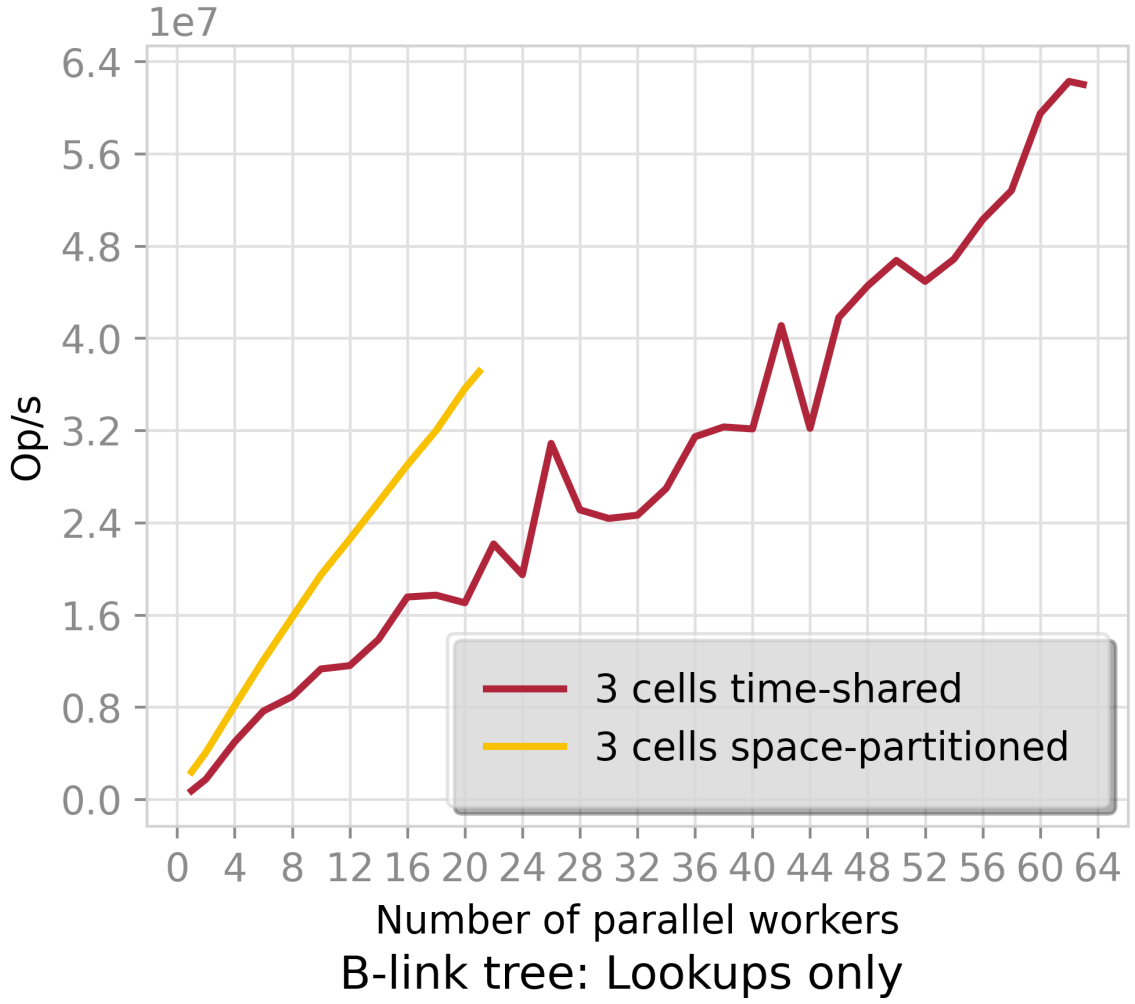
Repeat for blinktree2 and blinktree3

```
<config>
   <affinity-space width="64" height="1"/>
   <start name="timer">
          <provides><service name="Timer"/></provides>
      <route>
          <any-service><parent/><any-child/></any-
service>
      </route>
   </start>
   <start name="blinktree1">
      <affinity xpos="1" ypos="0" width="63"
height="1"/>
      <resource name="RAM"
quantum="80G"/>
      <binary name="blinktree"/>
      <route>
         <service name="Timer"><child
name="timer"/></service>
         <any-service><parent/><any-child/></any-
service>
      </route>
   </start>
   <start name="blinktree2">
      <binary name="blinktree"/>
   </start>
   <start name="blinktree3">
      <binary name="blinktree"/>
   </start>
</config>
```

Example: Results



B-link tree: Inserts only

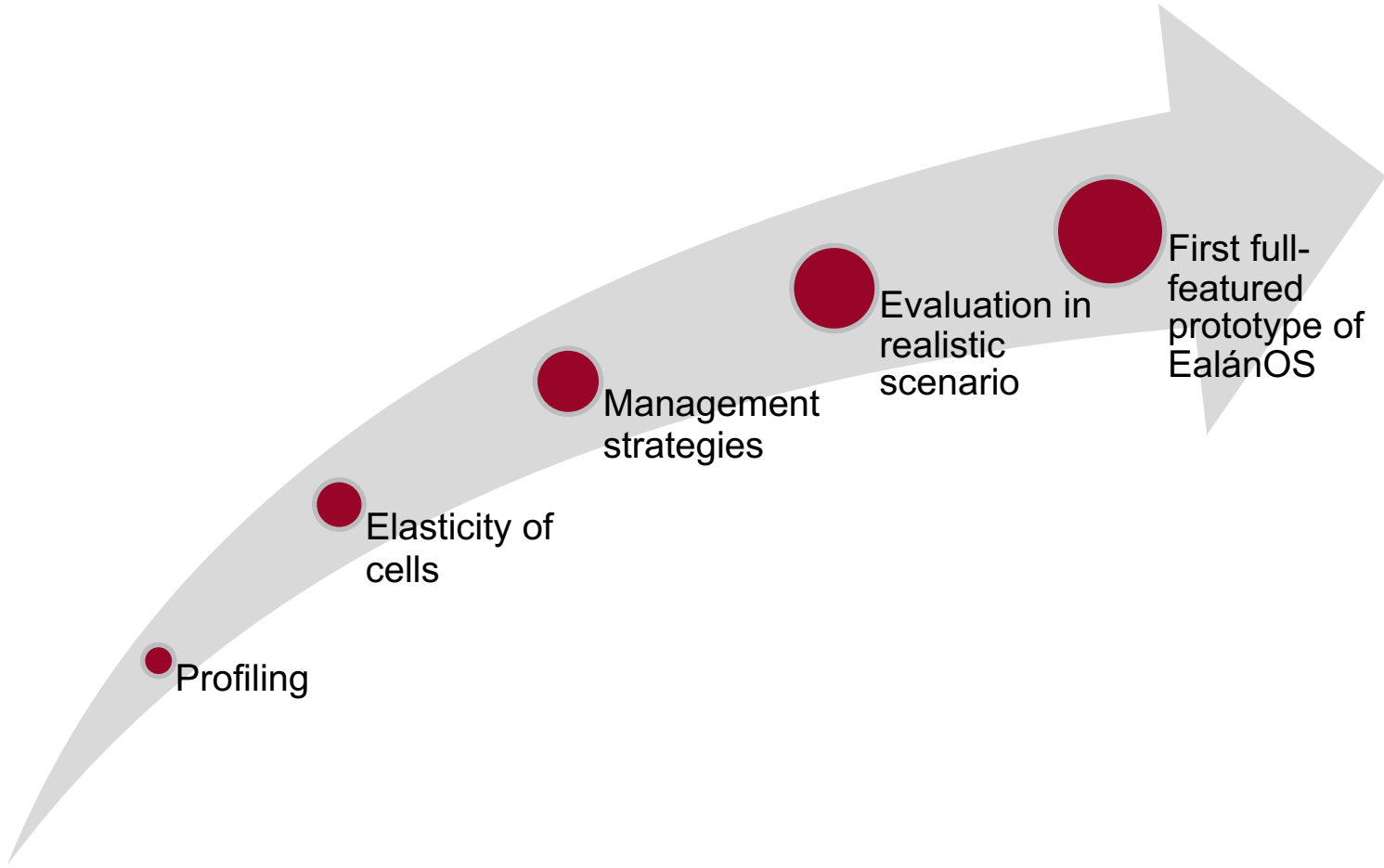


B-link tree: Lookups only

Conclusion

- Hardware has changed **tremendously**
- **More** OS research needed, but **high** entrance hurdle
- An OS framework can **lower** this barrier
- Genode can save up to **92% of** development **time**
- EalánOS **contributes to** Genode by offering
  - State-of-the art **task-parallel** programming
  - **NUMA** support
  - Support for **many-core** systems
- With a **focus** on research and the **datacenter**

The road to the future



- github.com/mmueller41/genode
- github.com/mmueller41/NOVA

EalánOS

- github.com/jmuehlig/mxtasking
- dbis.cs.tu-dortmund.de

MxTasking

Get in touch

Embedded Software Systems

- ess.cs.uos.de
- www.uni-osnabrueck.de

SPP2037

SCALABLE DATA MANAGEMENT FOR FUTURE HARDWARE

- mxkernel.org
- dfg-spp2037.org