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THE HETEROGENEOUS SYSTEMS EXPERTS

Towards Heterogeneous and Distributed Computing in C++

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DHPCC++ – May 2019

About me...

- Background in C++ programming models for heterogeneous systems
- Developer with Codeplay Software for 7 years
- Worked on ComputeCpp (SYCL) for 6 years
- Contributor to the Khronos SYCL standard since its inception
- Contributor to ISO C++ executors and heterogeneity for over 3 years

Contributors

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Agenda

What are C++ executors?

Properties

Oneway executors

Twoway executors

Supporting affinity

Standard / proprietary libraries

SYCL invoke define_task_block parallel algorithms future::then post

Kokkos defer async dispatch asynchronous operations strand<>

Executors

Unified executor interface

Third-party / OS hardware abstractions

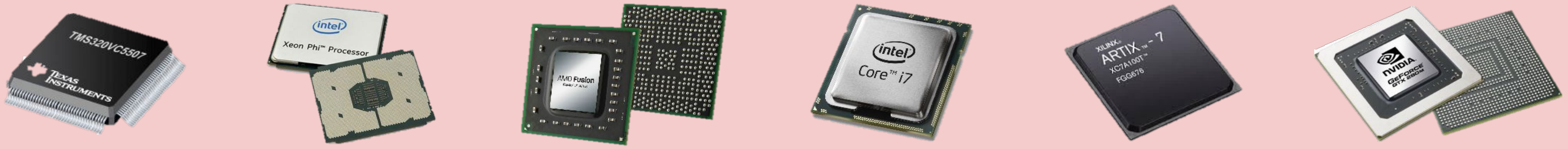
OpenCL / CUDA / HCC / HMM

OpenMP / MPI

OS threads

Boost.Asio / Networking TS

Hardware resources



```
auto fut = std::async(factorial, input);
auto res = fut.get();
```

```
auto fut = std::async(factorial, input);
auto res = fut.get();
```

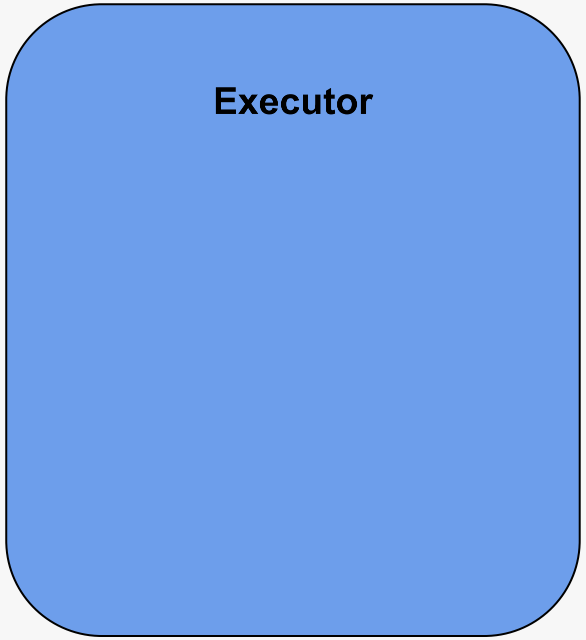
```
auto fut = std::async(gpu_executor{}, factorial, input);
auto res = fut.get();
```

```
std::sort(par, data.begin(), data.end());
```

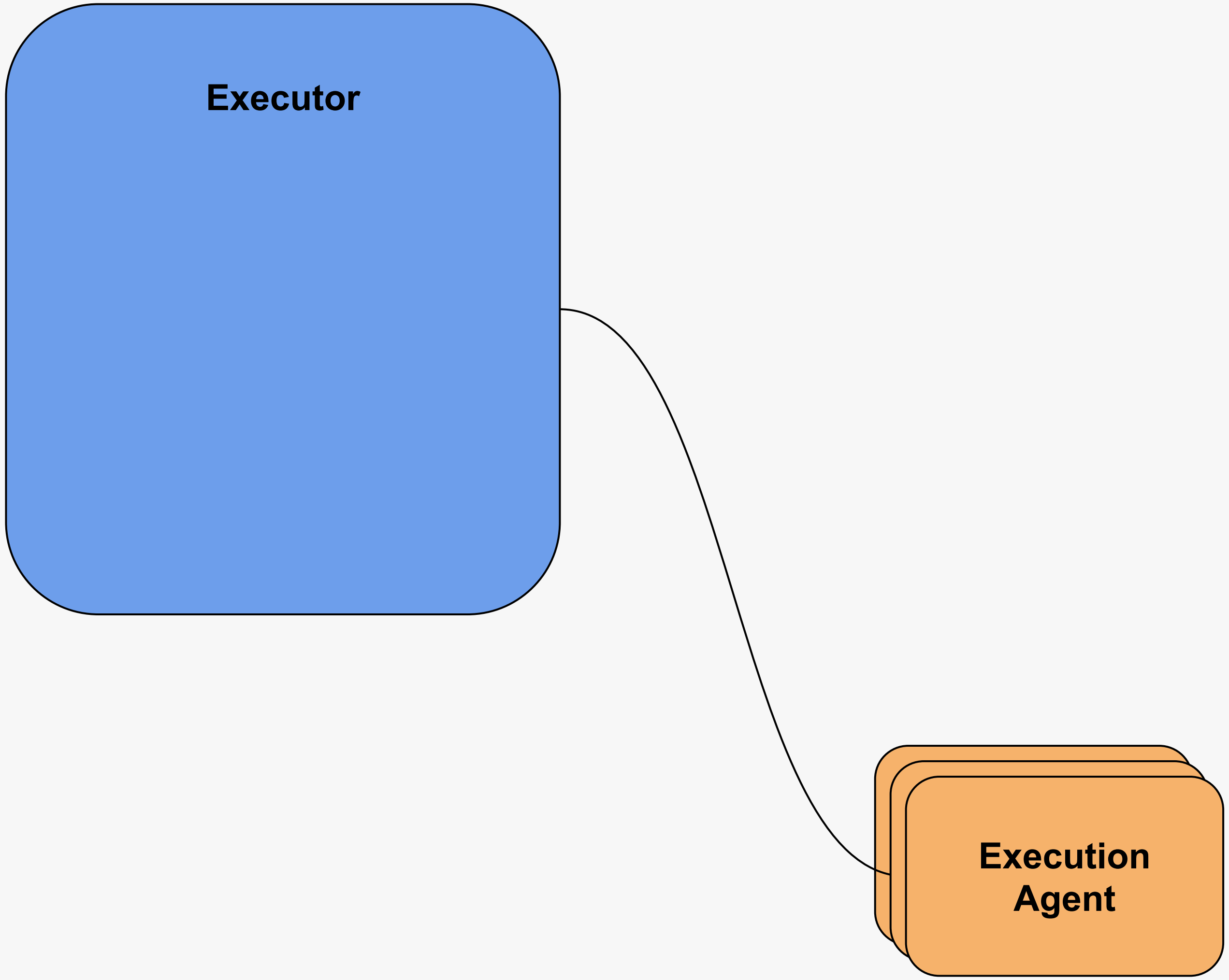
```
std::sort(par, data.begin(), data.end());
```

```
std::sort(par.on(gpu_executor{}), data.begin(), data.end());
```

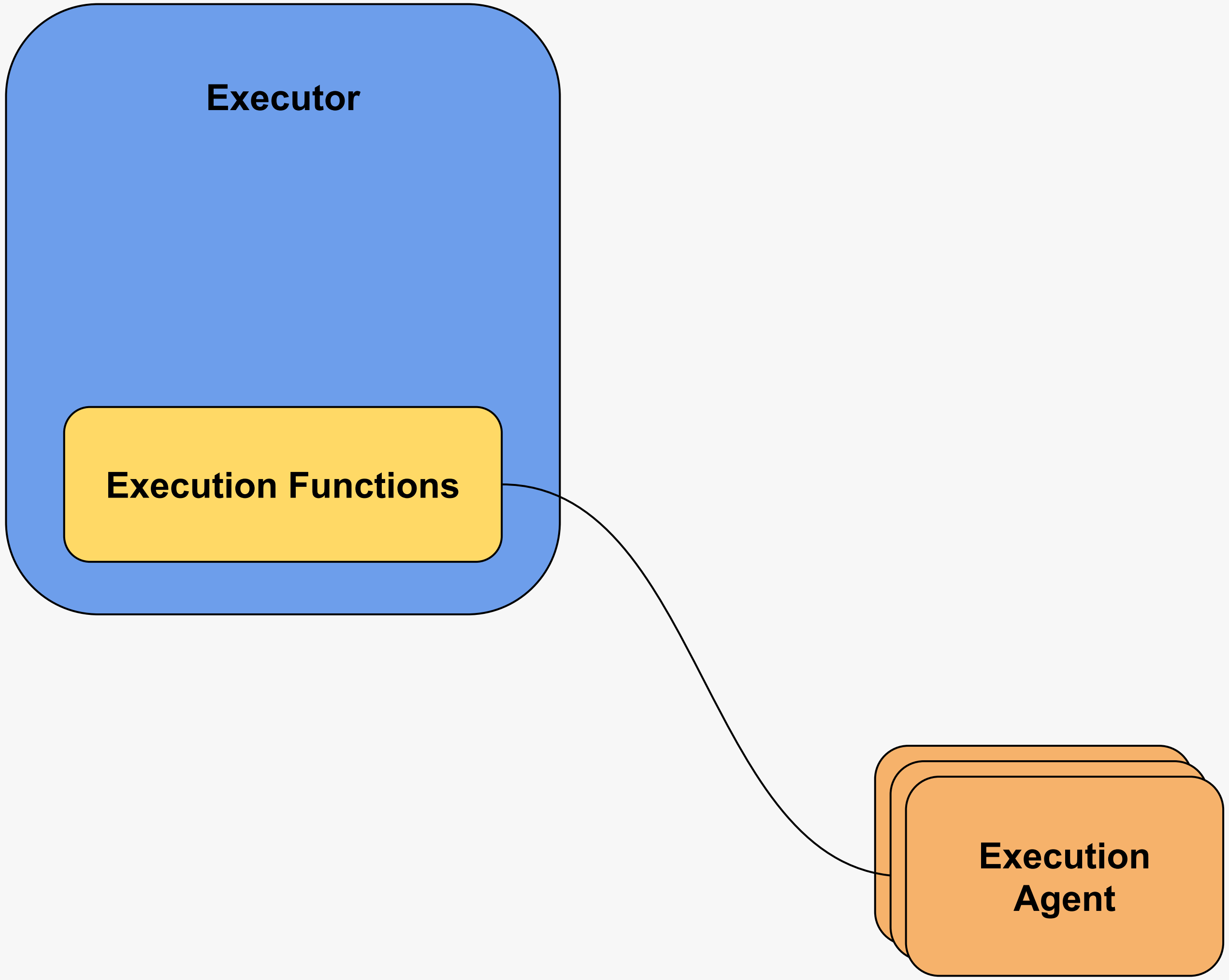
- An **executor** is an light-weight object



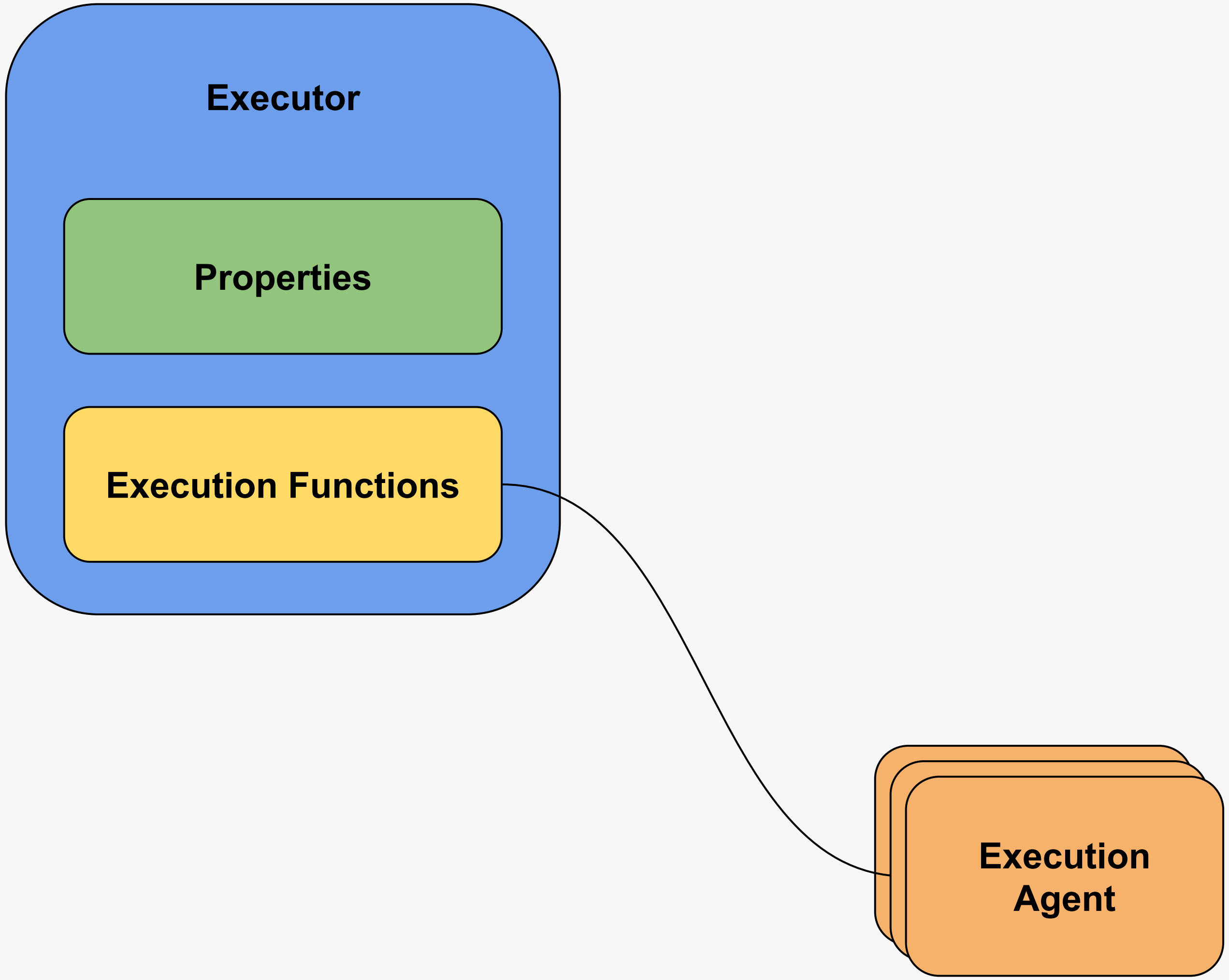
- An **executor** is an light-weight object
- It creates **execution agents** that invoke a callable



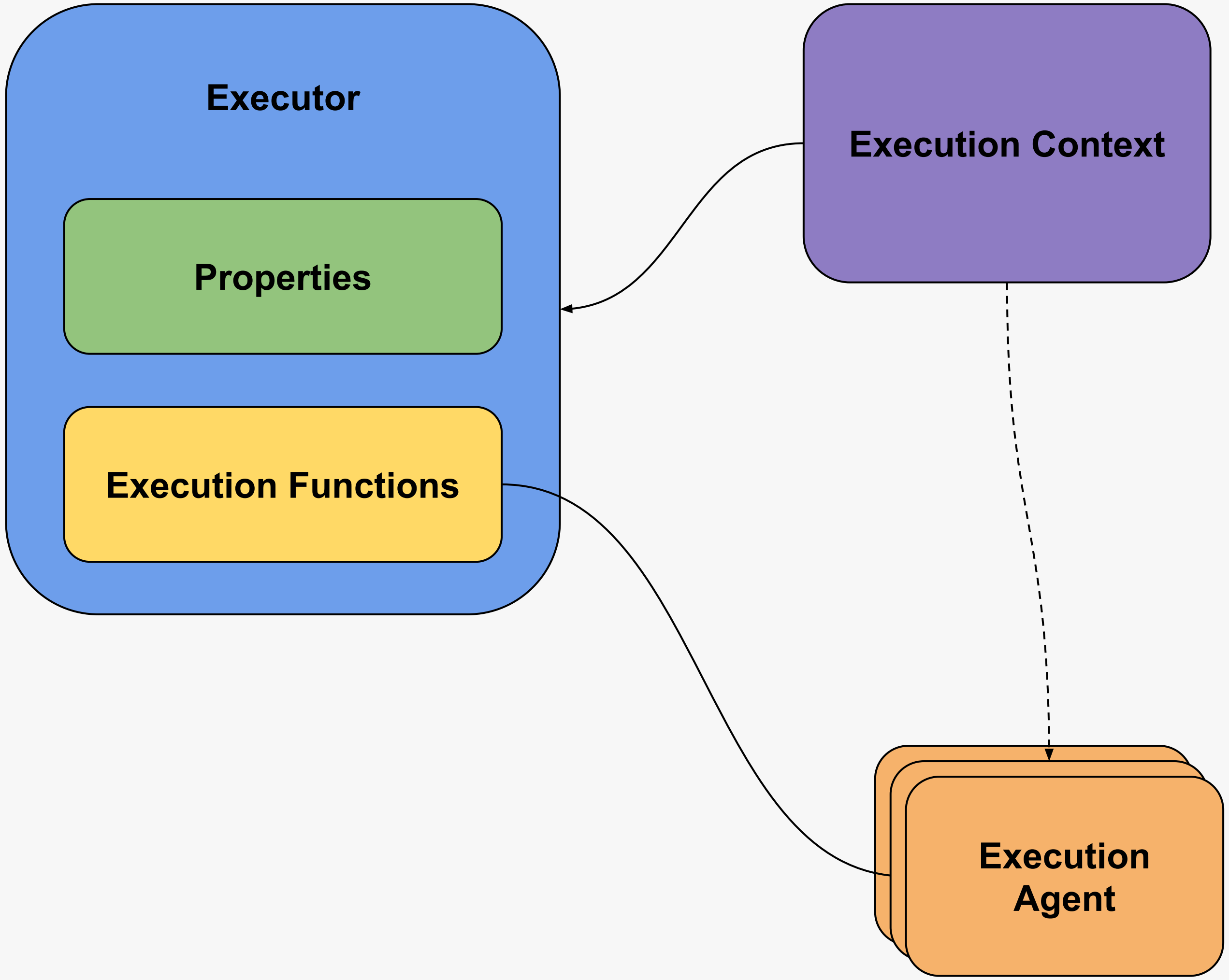
- An **executor** is an light-weight object
- It creates **execution agents** that invoke a callable
- It has a number of **execution functions** which provide different way of creating **execution agents**



- An **executor** is an light-weight object
- It creates **execution agents** that invoke a callable
- It has a number of **execution functions** which provide different way of creating **execution agents**
- It has a number of **properties** associated with it that dictate it's **execution functions** and the operational semantics of the **execution agents** it creates



- An **executor** is an light-weight object
- It creates **execution agents** that invoke a callable
- It has a number of **execution functions** which provide different way of creating **execution agents**
- It has a number of **properties** associated with it that dictate it's **execution functions** and the operational semantics of the **execution agents** it creates
- It is generally associated with an **execution context**, which manages the **execution agents** it creates



Agenda

What are C++ executors?

Properties

Oneway executors

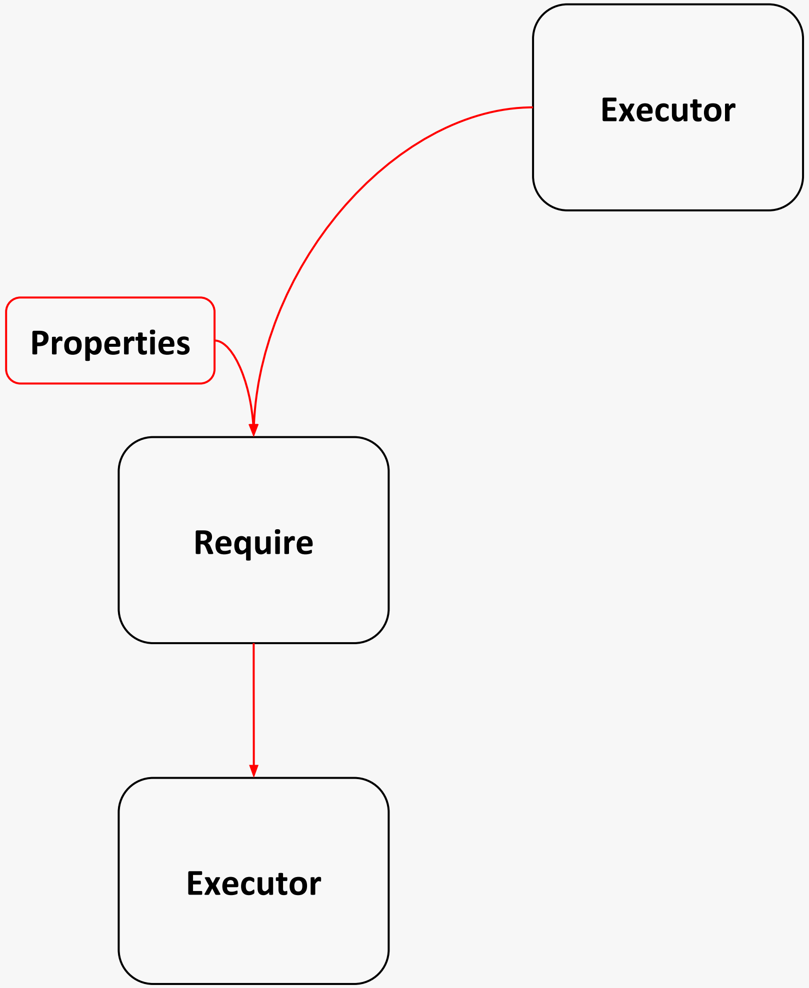
Twoway executors

Supporting affinity

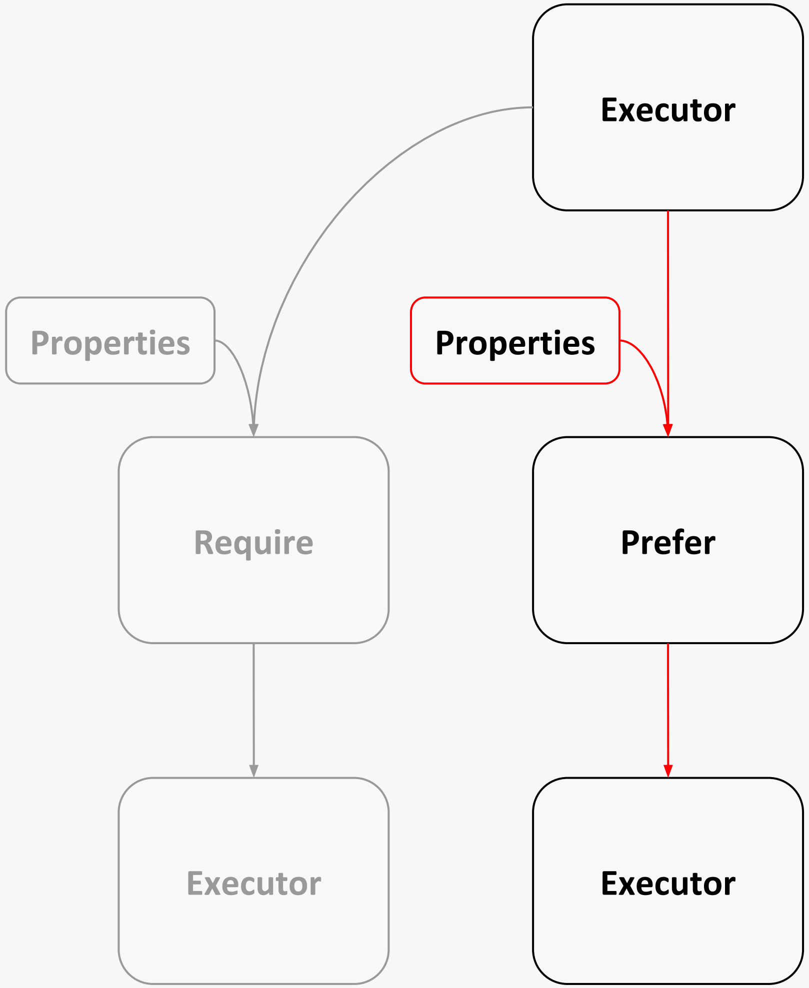
- Properties provide a software abstraction for executors to express the relationship between algorithm requirements and hardware capabilities
  - They allow you to require that an executor support a property
  - They allow you to query the value of an executor property

- This facilitates better performance portability in algorithm design
  - Different layers of an algorithm can be specialized or adapted based on executor properties

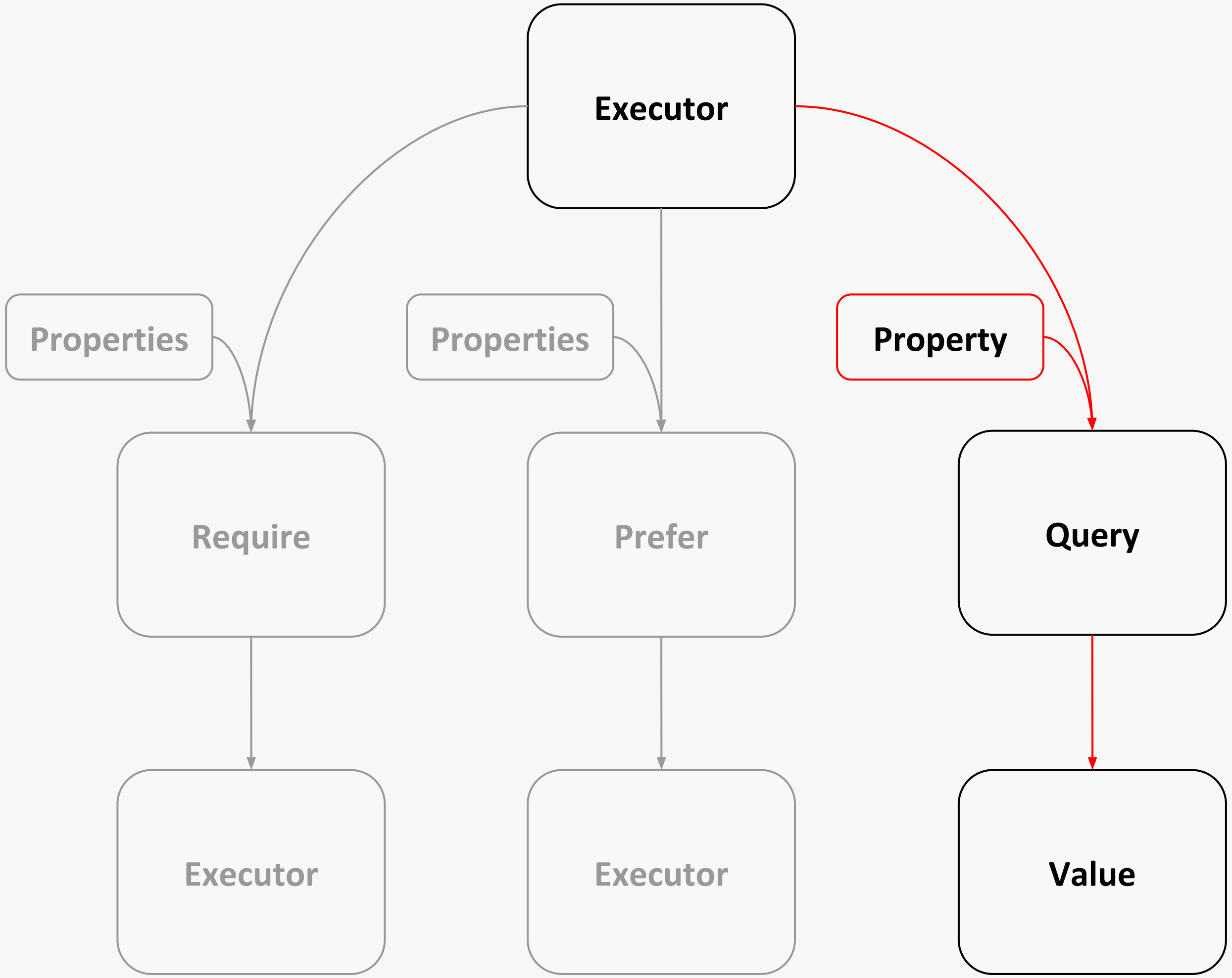
- Performing a require returns an executor that will have the requested properties
  - If the properties are already supported the original executor is returned
  - If the properties are not supported this will result in a compile-time error



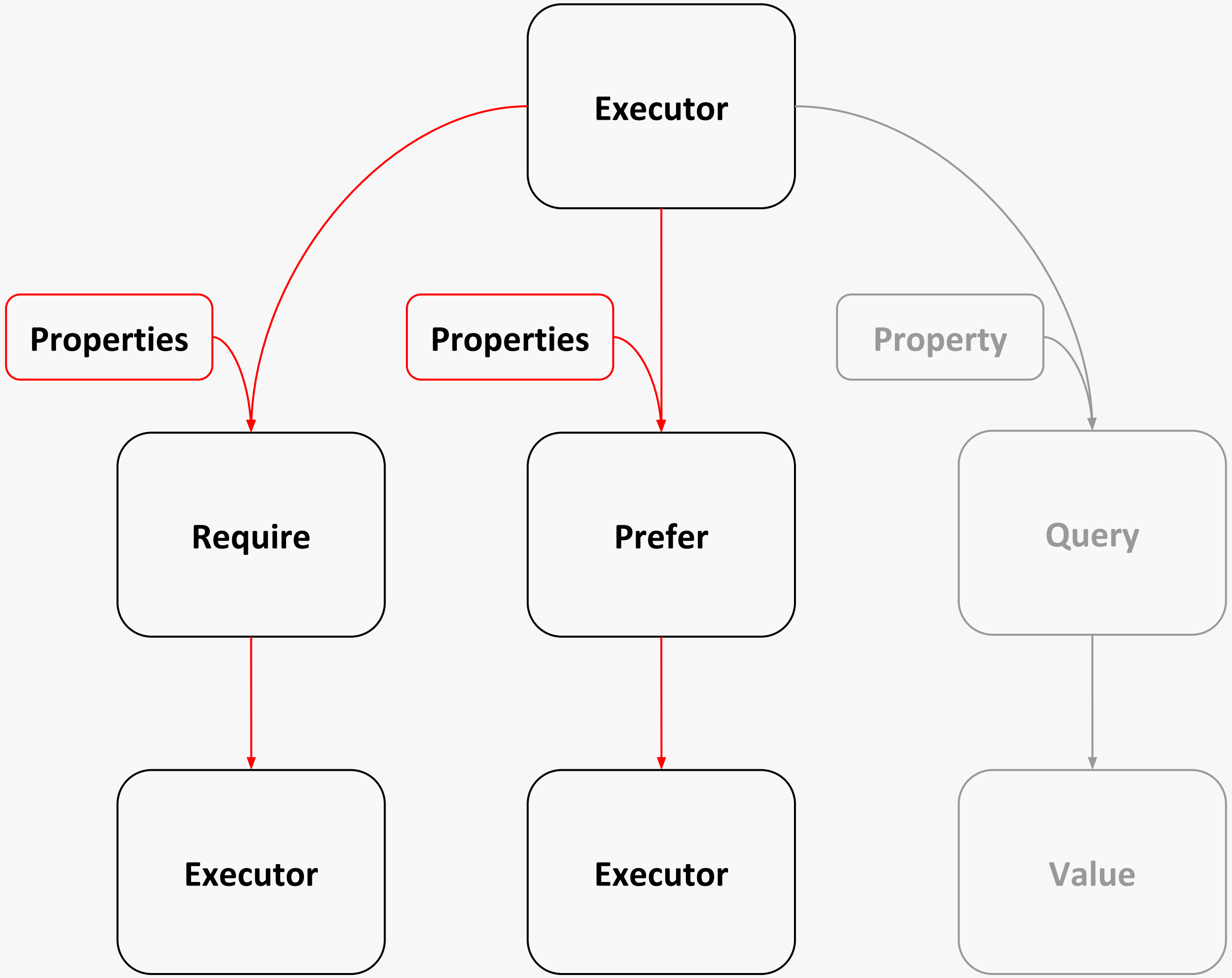
- Performing a prefer returns an executor that may have the requested properties
  - If the properties are already supported the same executor is returned
  - If the properties are not supported the executor will simply return the original executor



- Performing a query returns the current value of a specific property
  - In many cases this value will be a boolean
  - In some cases this query can be performed at compile-time if property::static_query_v is available



- Properties that are successfully requested via require or prefer can be supported in two ways
  - An executor implementation can natively support the property
  - An executor can support a property via an adaptation



```
oneway_executor exec;

auto newExec = require(exec, blocking.never);  // Must return a non-blocking executor

auto fut = newExec.execute(func);
```

Require

```
oneway_executor exec;

auto newExec = require(exec, blocking.never);   // Must return a non-blocking executor

auto fut = newExec.execute(func);
```

Require

```
oneway_executor exec;

auto newExec = prefer(exec, blocking.never);  // May or may not return a non-blocking executor

newExec.execute(func);
```

Prefer

```
oneway_executor exec;

auto newExec = require(exec, blocking.never);   // Must return a non-blocking executor

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Require

```
oneway_executor exec;

auto newExec = prefer(exec, blocking.never );  // May or may not return a non-blocking executor

newExec.execute(func);
```

Prefer

```
oneway_executor exec;

auto newExec = prefer(exec, blocking.never);  // May or may not return a non-blocking executor

auto isNonBlocking = query(newExec, blocking.never);
```

Query

Agenda

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Supporting affinity

- Oneway executors provide execution functions which execute a callable without a communication channel
    - Eager “Fire and forget” execution
    - No return value
    - Synchronisation and error handling are managed via another channel

- Single and bulk cardinality
    - Execute a callable exactly once on a single execution agent
    - Execute a callable in multiple iterations on multiple execution agents

```
oneway_executor exec;

exec.execute([&]() {
  ...
});
```

Single

```
oneway_executor exec;

exec.execute([&]() {
  ...
});
```

Single

```
bulk_executor exec;

exec.bulk_execute([&](index<N> i,
  auto r, auto s){
  ...
}, shape, resultFactory, sharedFactory);
```

Bulk

Agenda

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Twoway executors

Supporting affinity

- Twoway executors provide an execution functions which execute a callable with a communication channel
  - Propagates a return value or an error
  - Provides a predicate to later callables

- Sender/receiver model
  - Lazy generalization of futures and promises
    - Sender: lazy future
    - Receiver: lazy promise
  - Composition of nested callables
  - Communication channel doesn’t require shared state allocation or synchronization

`Execute f on the CPU, then execute g on the GPU`

Execute **f** on the CPU, then execute **g** on the GPU

```
auto s1 = take(42);
auto s2 = transform(s1, f);
auto s3 = via(s2, gpu_executor{});
auto s4 = transform(s3, g);
s4.submit(receiver{&res});
```

```
auto s1 = take(42);
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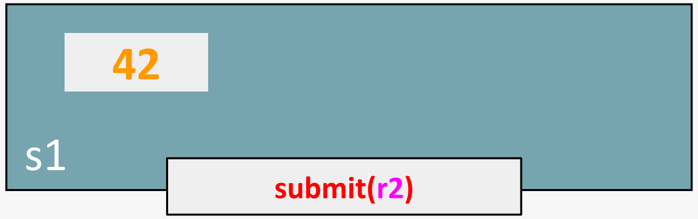

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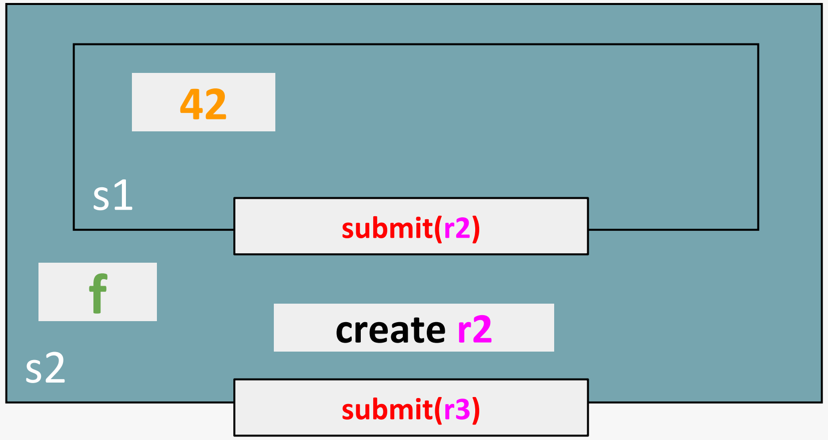

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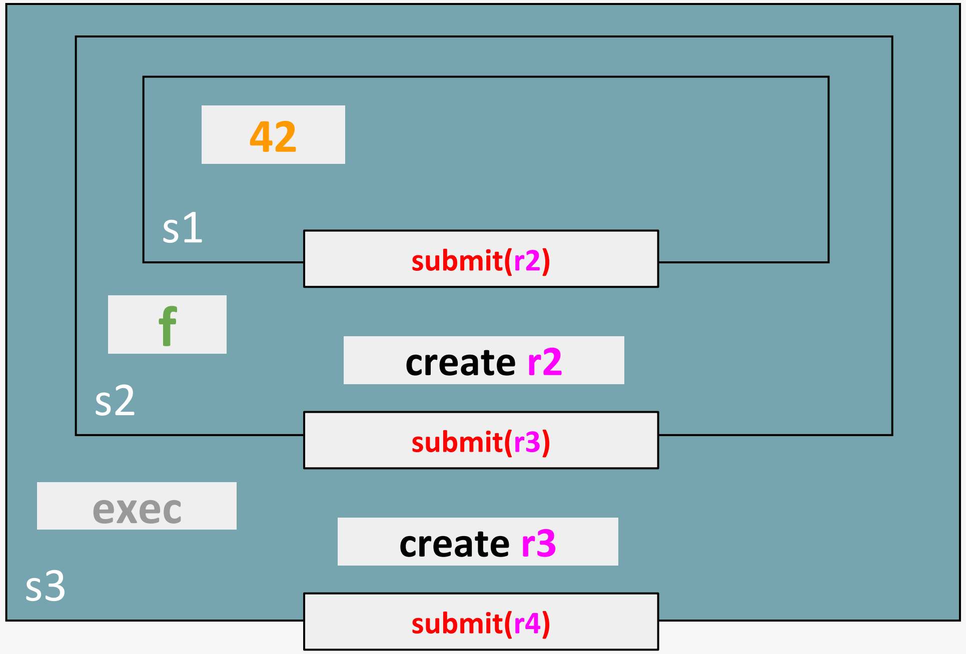

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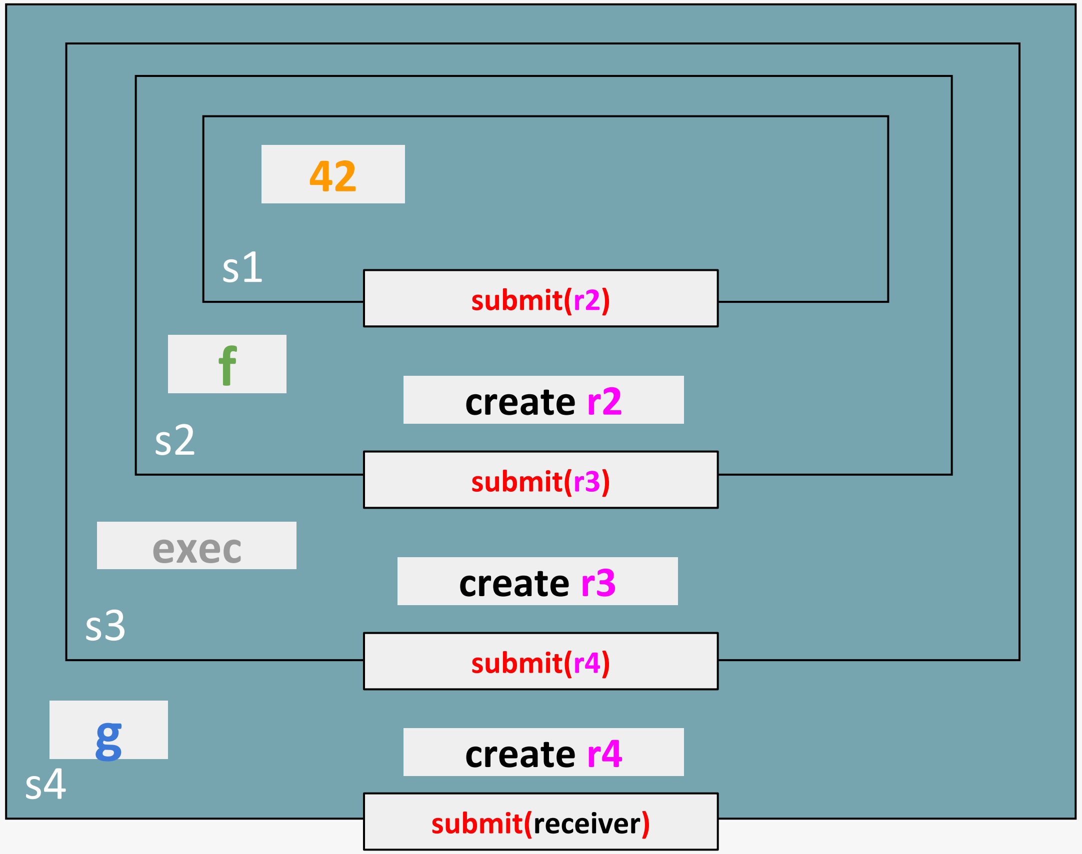

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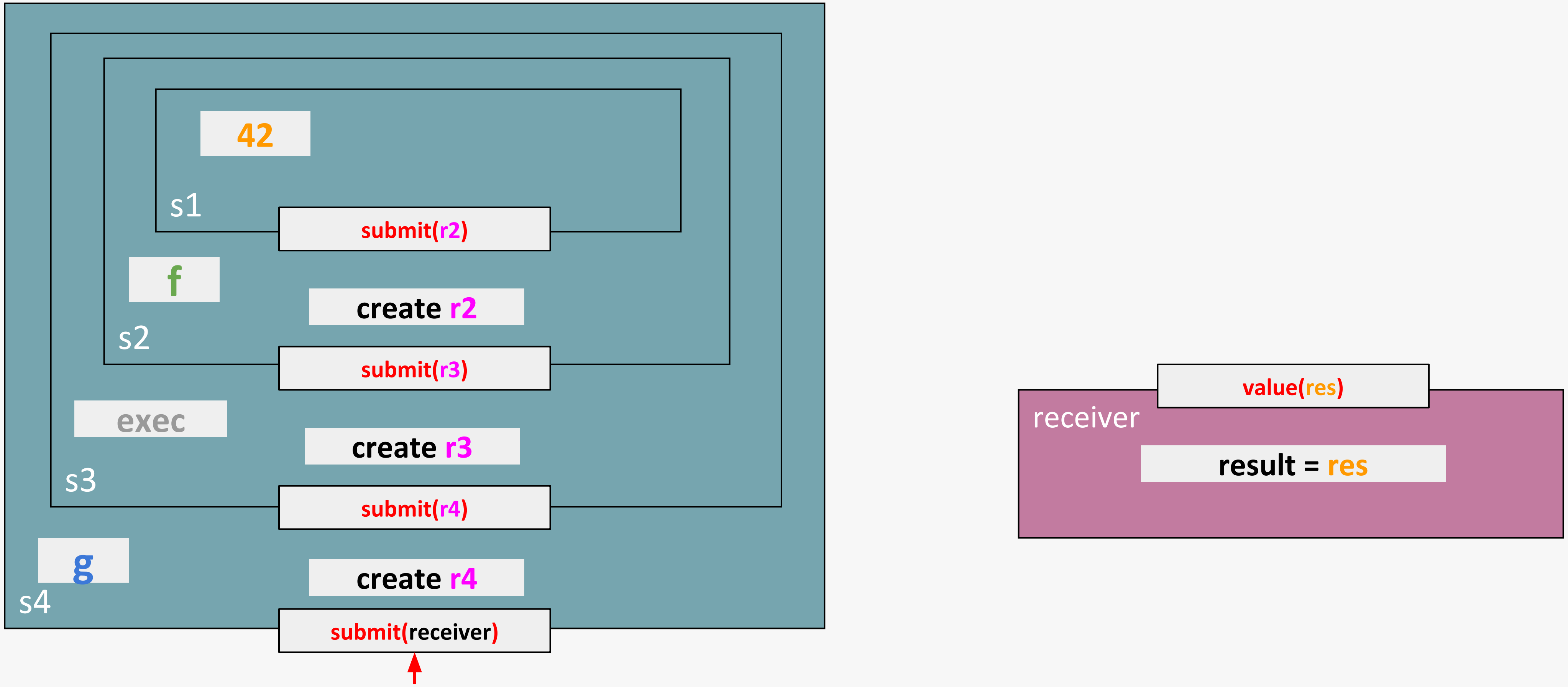

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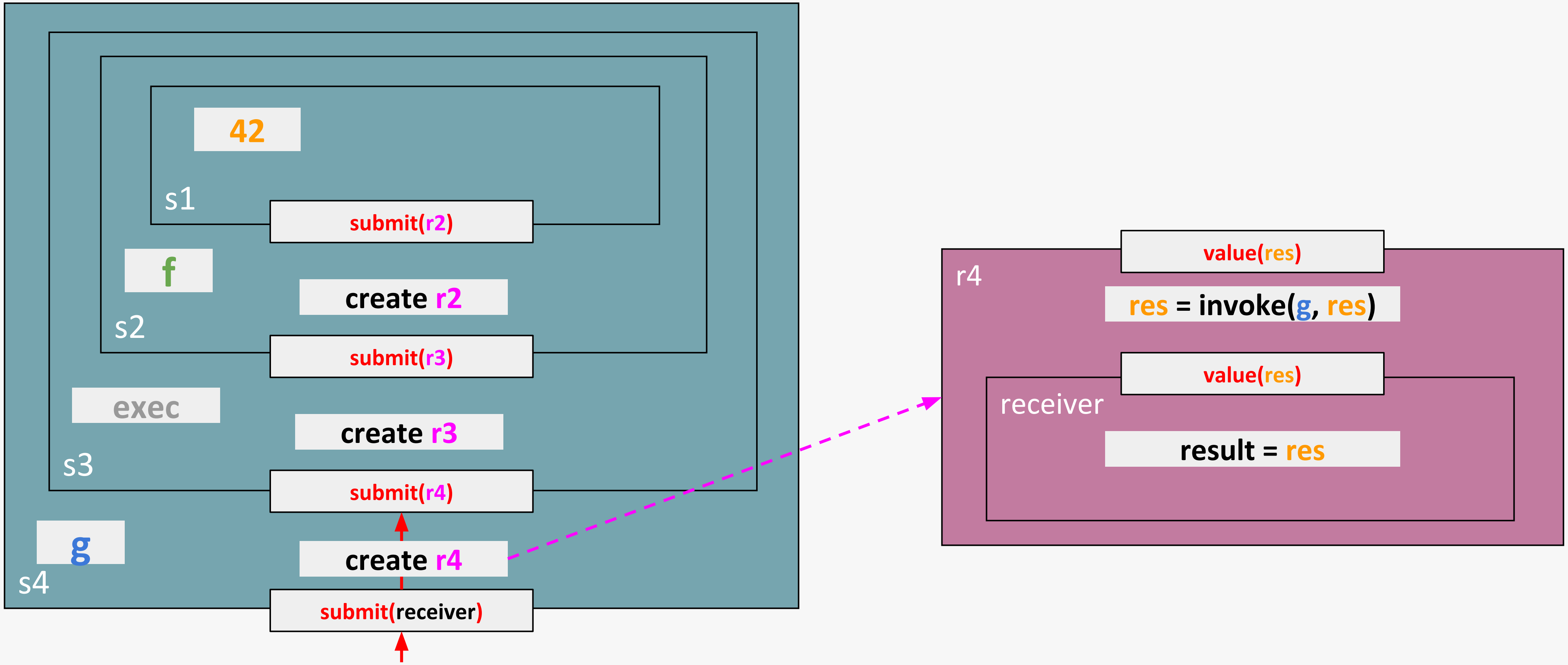

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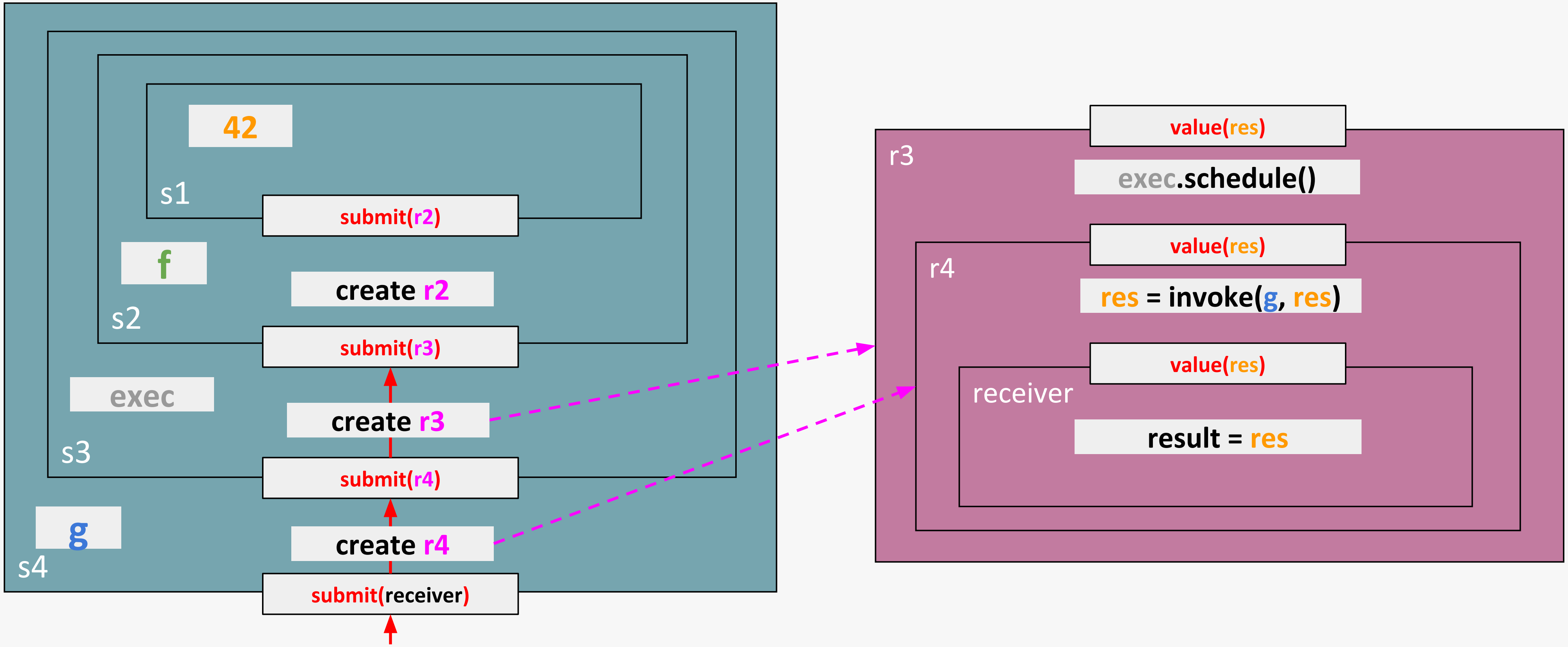

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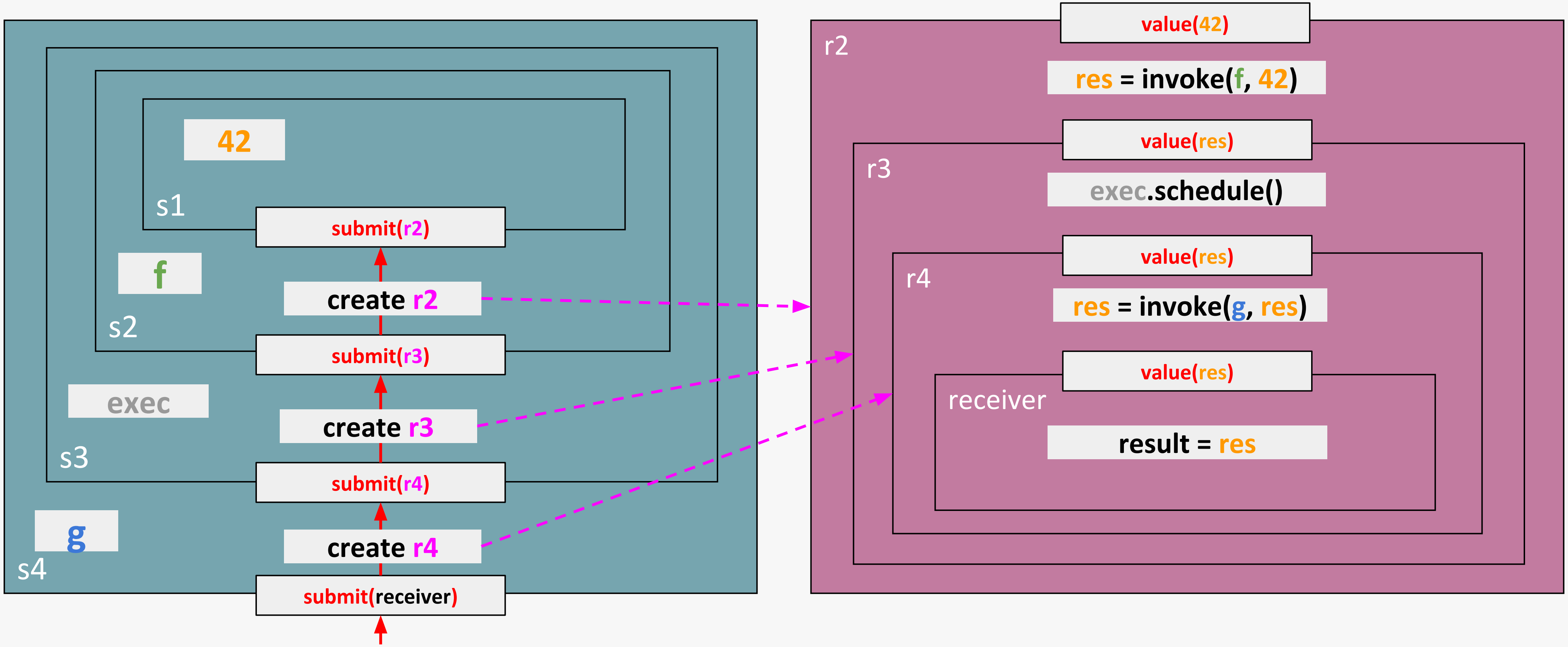

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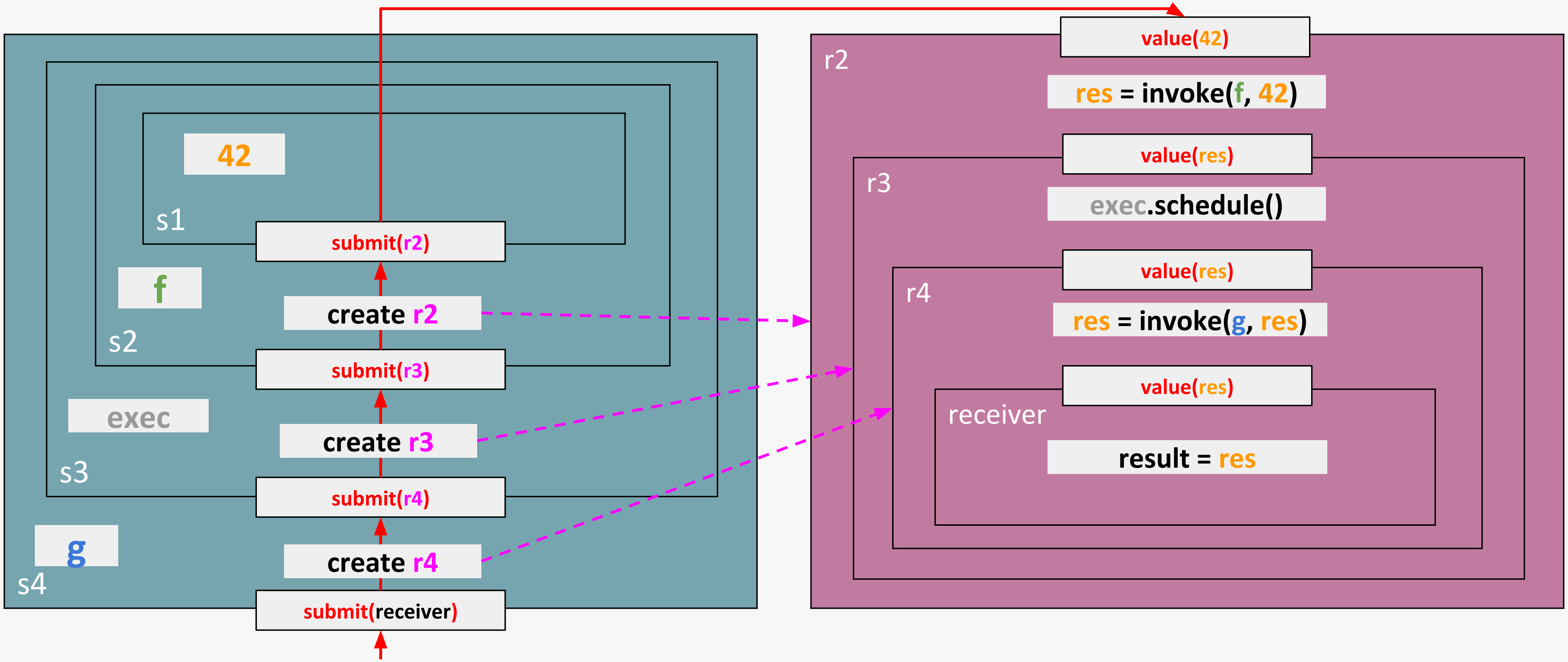

42

s1

submit(r2)

f

create r2

s2

submit(r3)

exec

create r3

s3

submit(r4)

g

create r4

s4

submit(receiver)

value(42)

r2

res = invoke(f, 42)

value(res)

r3

exec.schedule()

value(res)

r4

res = invoke(g, res)

value(res)

receiver

result = res

```
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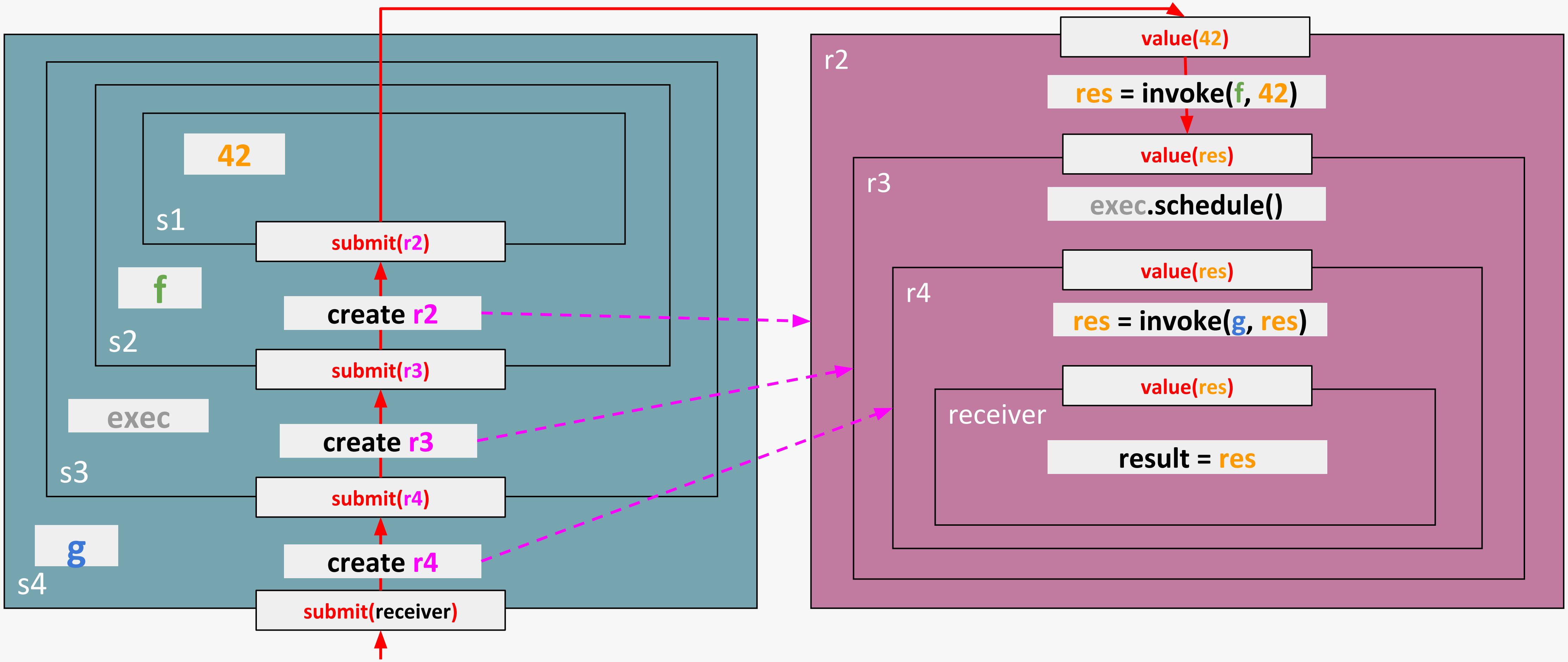

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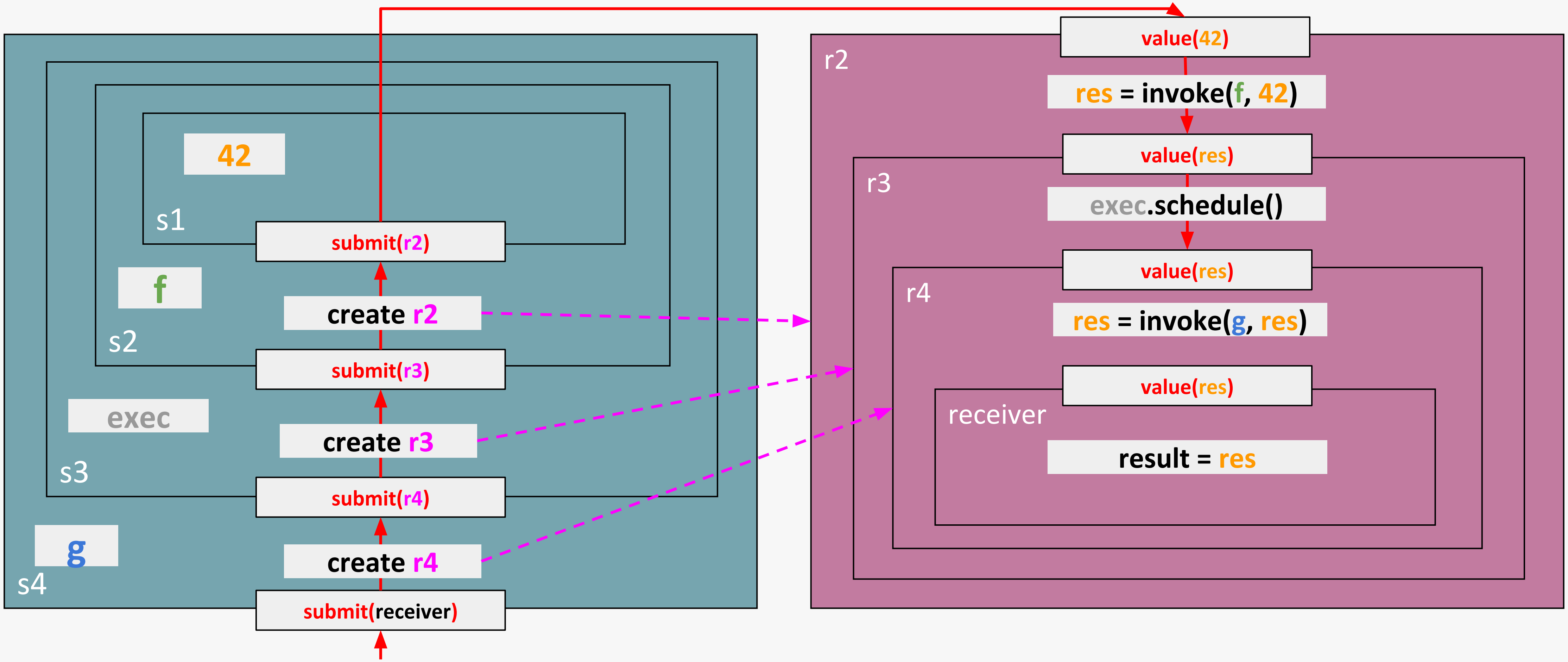

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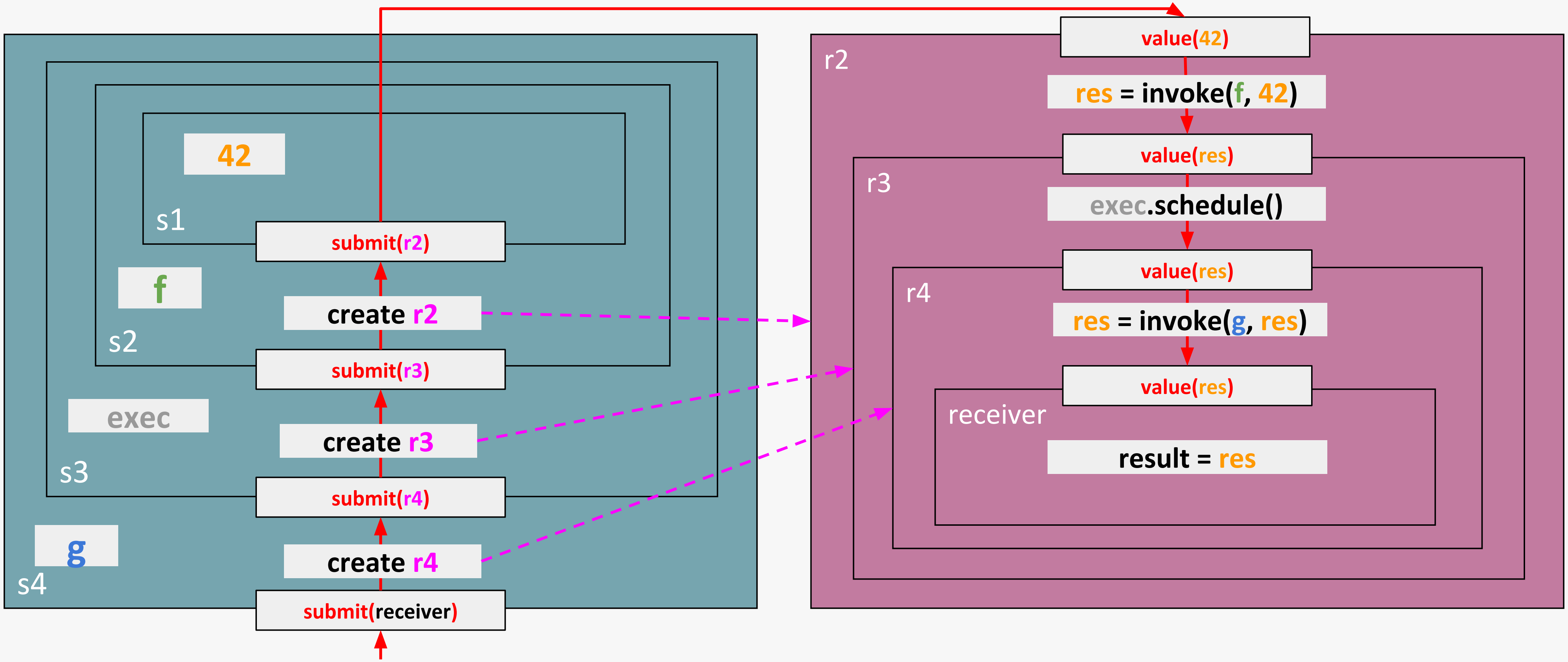

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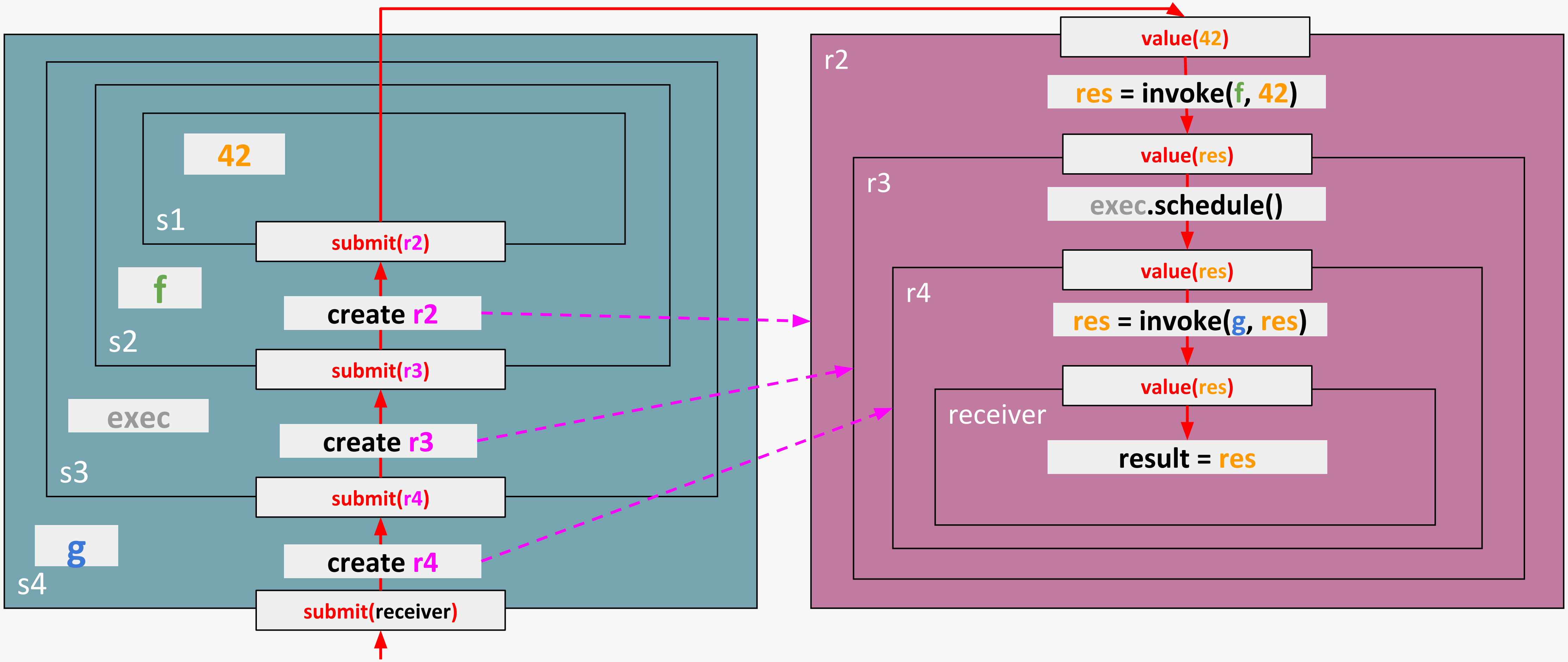

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P0796: Supporting Heterogeneous & Distributed Computing Through Affinity

High-level

P1436: Executor properties for affinity-based execution

Low-level

P1437: System topology discovery for heterogeneous & distributed computing (WIP)

- All systems are inherently heterogeneous
    - Desktop systems commonly have compute capable co-processors design for specific tasks such as GPUs or FPGAs
    - Server systems commonly have multiple CPU nodes or CPU + {GPU, FPGA, DSP, TPU, etc} nodes
    - Mobile and embedded SoC systems commonly have GPUs and/or often other specialised co-processors

- Many systems are distributed
    - HPC server and cloud systems have a distribution of a large number of interconnected nodes
    - These nodes can be connected physically or via network communication

- The structure of memory is no longer simple
    - Distributed memory regions across NUMA nodes
    - Hierarchical GPU memory regions
    - On-chip shared memory
    - Off-chip DMA transfers
    - Shared virtual memory through cache coherency
    - High Bandwidth Memory (HBM)
    - Persistent memory

- Memory allocation has to be adjusted to gain performance
    - Utilisation of shared memory regions (physical or virtual)
    - First touch memory allocation for lower latency access
    - Migration of memory allocations between discrete memory regions

- Define an interface for discovering and querying affinity
    - Solution must allow querying affinity related properties of an executor
    - Solution must provide process and memory affinity binding

- Integrate closely with the unified executors proposal (P0443)
    - Solution must align closely with the direction of the executors design

- Ensure scalability to heterogeneous and distributed systems
    - Solution needs to consider the limitations of heterogeneous and distributed systems to ensure scalability for future hardware

- The property **bulk_execution_affinity** requires that an executor provide a guaranteed affinity binding pattern
  - Pattern can be **none**, **balanced**, **scatter** or **compact**
  - Requires that each execution agent be bound to a particular execution resource before the callable is called
  - Binding must be consistent across all invocations of **bulk_execute** with the same size

<table>
<tr><td colspan="8">Socket 0</td><td colspan="8">Socket 1</td></tr>
<tr><td colspan="4">Core 0</td><td colspan="4">Core 1</td><td colspan="4">Core 0</td><td colspan="4">Core 1</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>3</td><td>0</td><td>1</td><td>2</td><td>3</td><td>0</td><td>1</td><td>2</td><td>3</td><td>0</td><td>1</td><td>2</td><td>3</td></tr>
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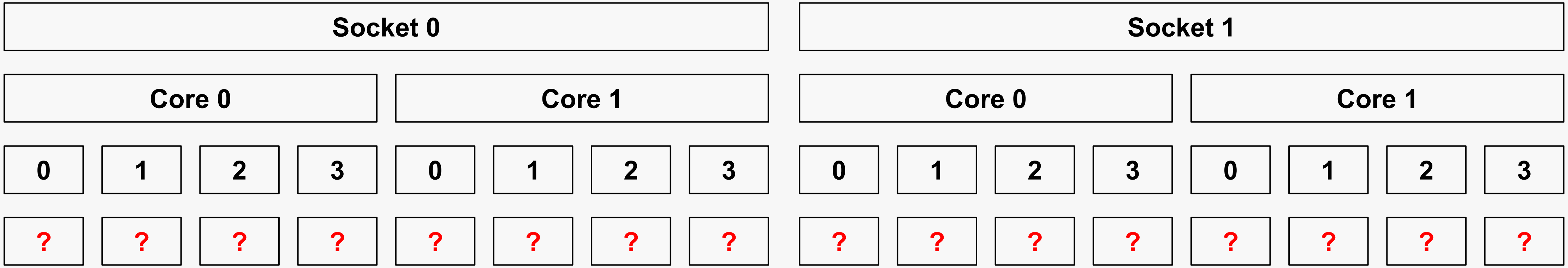
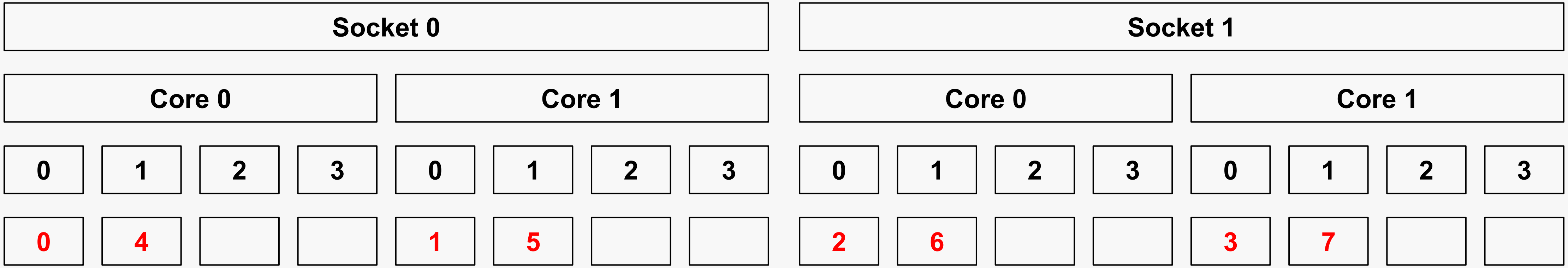


Socket 0								Socket 1							
Core 0				Core 1				Core 0				Core 1			
0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?

```
auto exec = execution::execution_context{execRes}.executor();

auto affExec = execution::require(exec, execution::bulk,
  execution::bulk_execution_affinity.none);

affExec.bulk_execute([](std::size_t i, shared s) {
  func(i);
}, 8, sharedFactory);
```

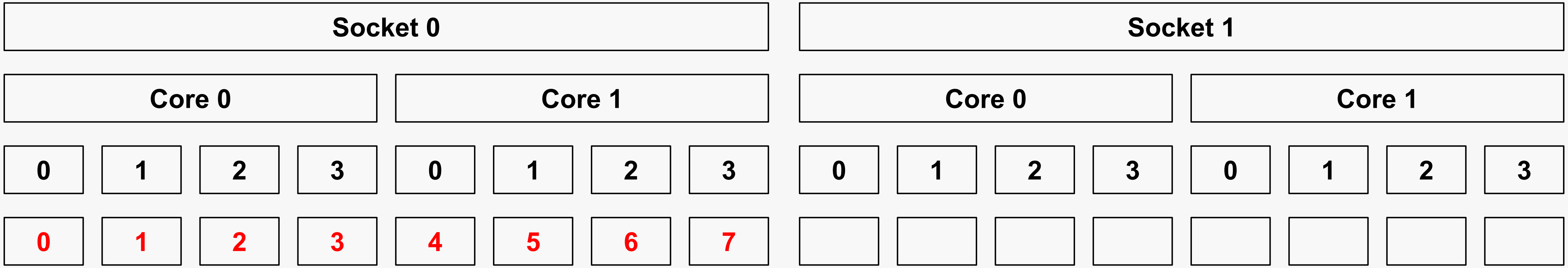


Socket 0								Socket 1							
Core 0				Core 1				Core 0				Core 1			
0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
0	4			1	5			2	6			3	7		

```
auto exec = execution::execution_context{execRes}.executor();

auto affExec = execution::require(exec, execution::bulk,
  execution::bulk_execution_affinity.scatter);

affExec.bulk_execute([](std::size_t i, shared s) {
  func(i);
}, 8, sharedFactory);
```

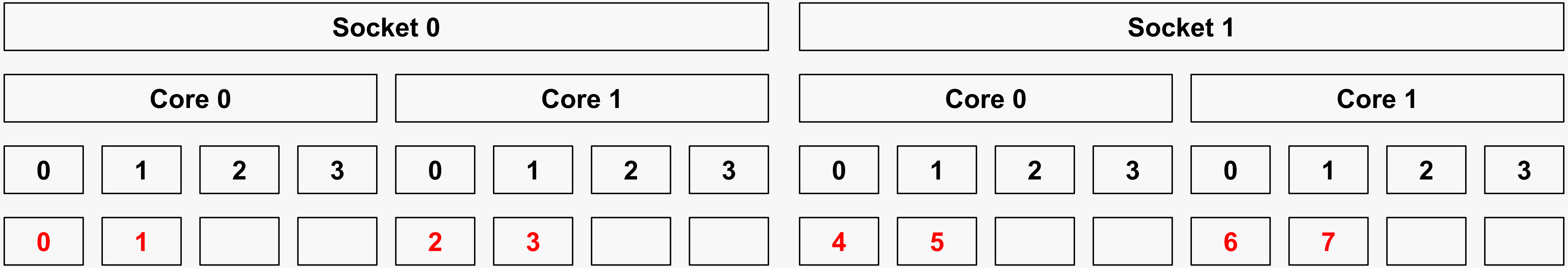


Socket 0								Socket 1							
Core 0				Core 1				Core 0				Core 1			
0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
0	1	2	3	4	5	6	7								

```
auto exec = execution::execution_context{execRes}.executor();

auto affExec = execution::require(exec, execution::bulk,
  execution::bulk_execution_affinity.compact);

affExec.bulk_execute([](std::size_t i, shared s) {
  func(i);
}, 8, sharedFactory);
```



Socket 0								Socket 1							
Core 0				Core 1				Core 0				Core 1			
0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
0	1			2	3			4	5			6	7		

```
auto exec = execution::execution_context{execRes}.executor();

auto affExec = execution::require(exec, execution::bulk,
  execution::bulk_execution_affinity.balanced);

affExec.bulk_execute([](std::size_t i, shared s) {
  func(i);
}, 8, sharedFactory);
```

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  - This provides a guide to the optimal bulk execution shape, but not a guarantee that

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```
executor exec;

size_t maxConcurrency = execution::query(exec, execution::concurrency);
```

- The query-only property **execution_locality_intersection** returns the maximum potential concurrency available to both of two executors
    - Tells you whether two executors will be contesting for the same resources

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  - Tells you whether two executors will be contesting for the same resources

```
executor_a execA;
executor_b execB;

size_t concurrencyOverlap = execution::query(execA,
  execution::execution_locality_intersection(execB));
```

- The query-only property **memory_locality_intersection** returns whether two execution resources share the same memory locality
  - Tells you whether memory allocated in each of the executors is in the same locale

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  - Tells you whether memory allocated in each of the executors is in the same locale

```
executor_a execA;
executor_b execB;

bool concurrencyOverlap = execution::query(execA,
  execution::memory_locality_intersection(execB));
```

Conclusions

- Executors did not make C++20
    - It was decided that some features need more time to bake before being ready for the standard

- So targeting C++23, what will executors look like?
    - There will be a properties mechanism, likely as seen in P0443
    - There will be oneway “fire and forget” executors, likely as seen in P0443
    - There will be twoway “sender/receiver” executors, likely to be along the lines of P1341
    - We hope there will be properties for affinity based allocation and execution, along the lines of P1436

- Some useful links:
    - Current unified executors proposal - http://wg21.link/p0443
    - Sender/receiver executors - http://wg21.link/p1341
    - Executor properties for affinity - https://wg21.link/p1436

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Thanks for listening