C++ in the World of Embedded Systems

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Cppcon
The C++ Conference
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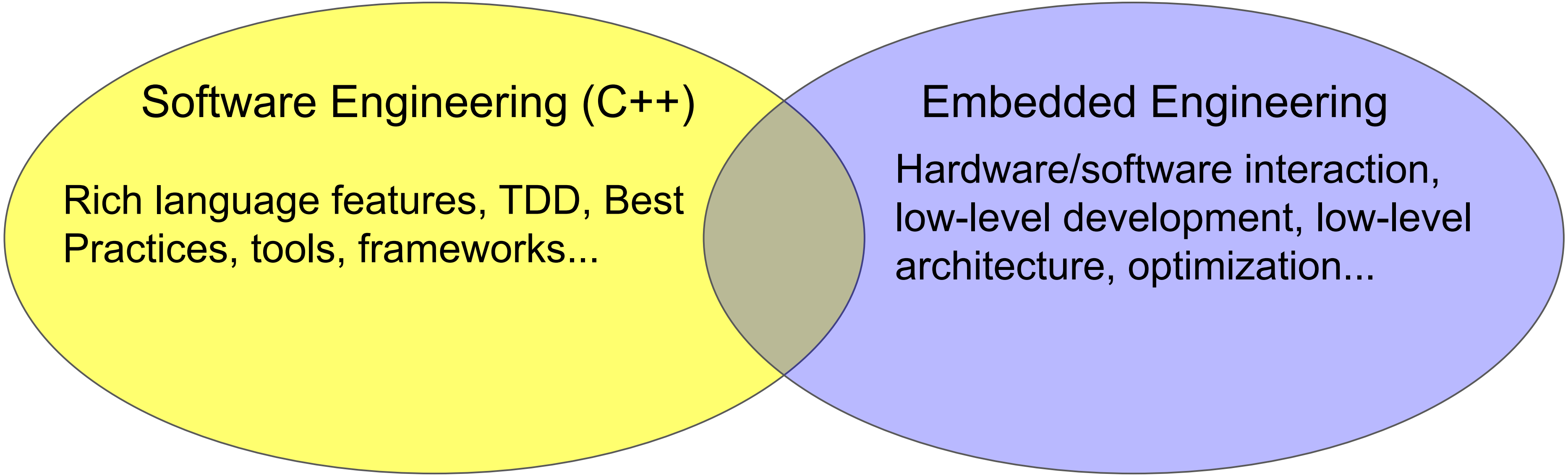
Agenda

1. Overview of embedded systems
2. Typical architectures in embedded systems
3. Review of the C++ availability, applicability and potential for embedded environments
4. Examples of C++ application for embedded code development

Motivation

Encourage knowledge and experience exchange between software engineering and embedded development.



Embedded systems

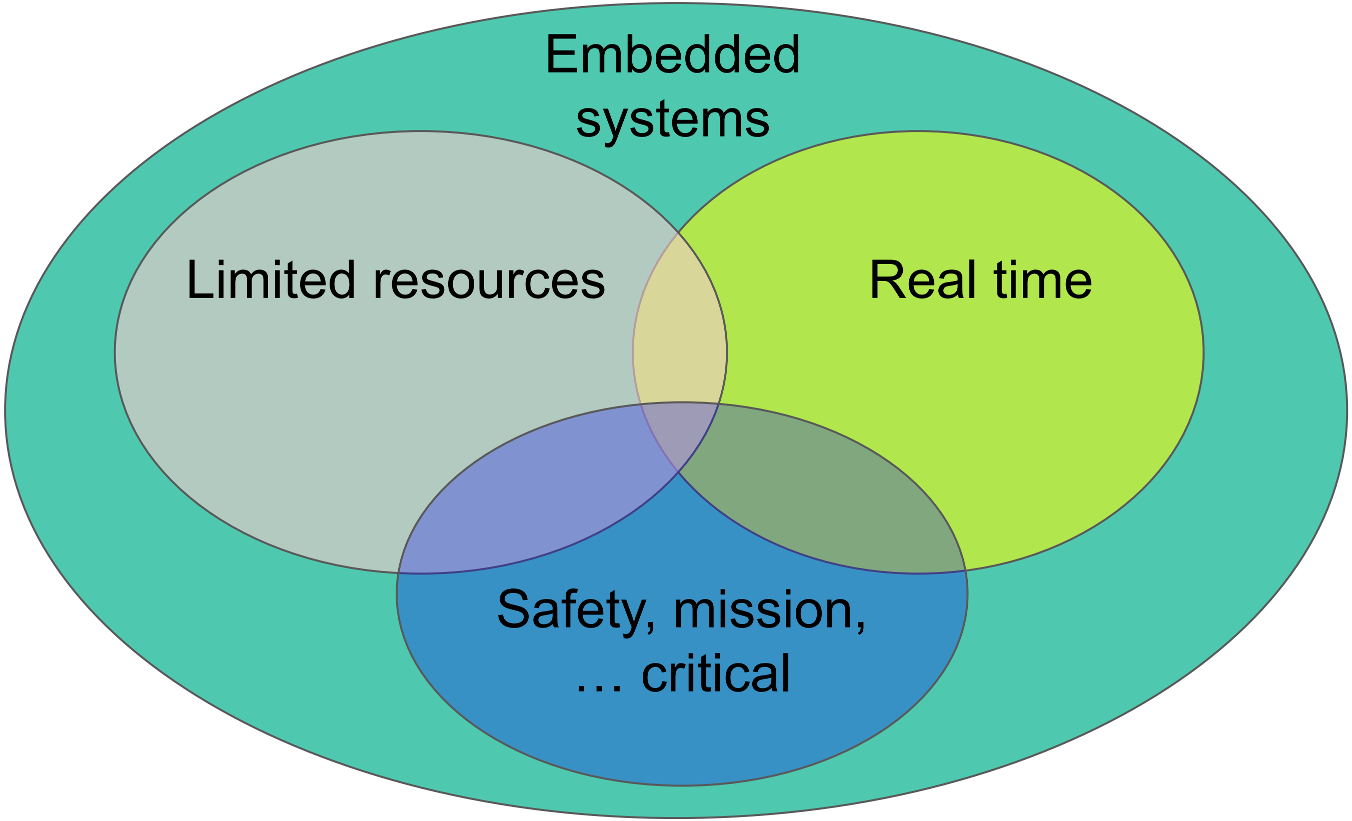
Non-formal definition:

An embedded (computer) system is a **specialized** computer system **designed as a part of another system**

Examples:

Electronic control units (ECU) in automotive, control elements in “smart” devices, etc.

Embedded systems categories



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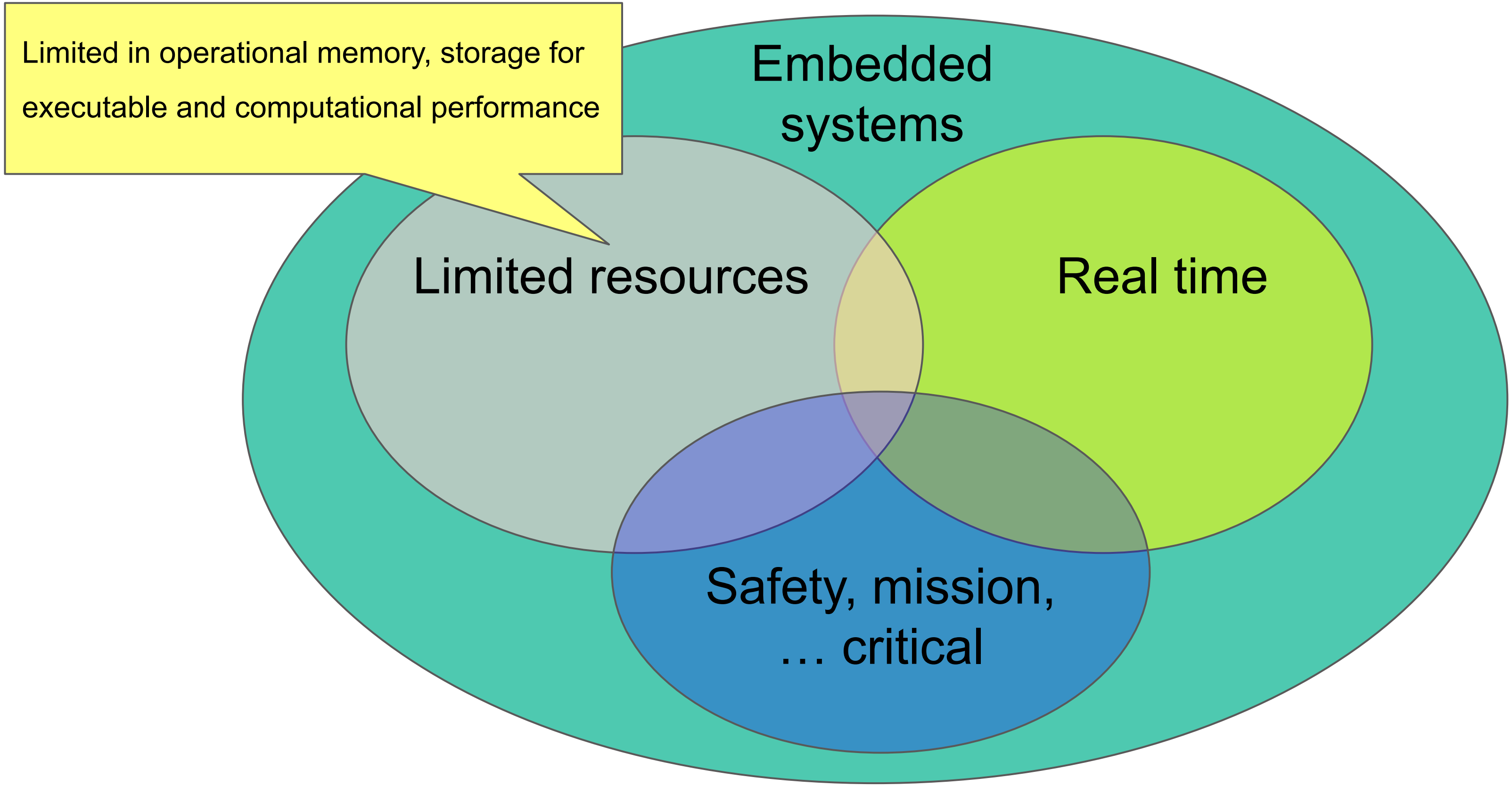

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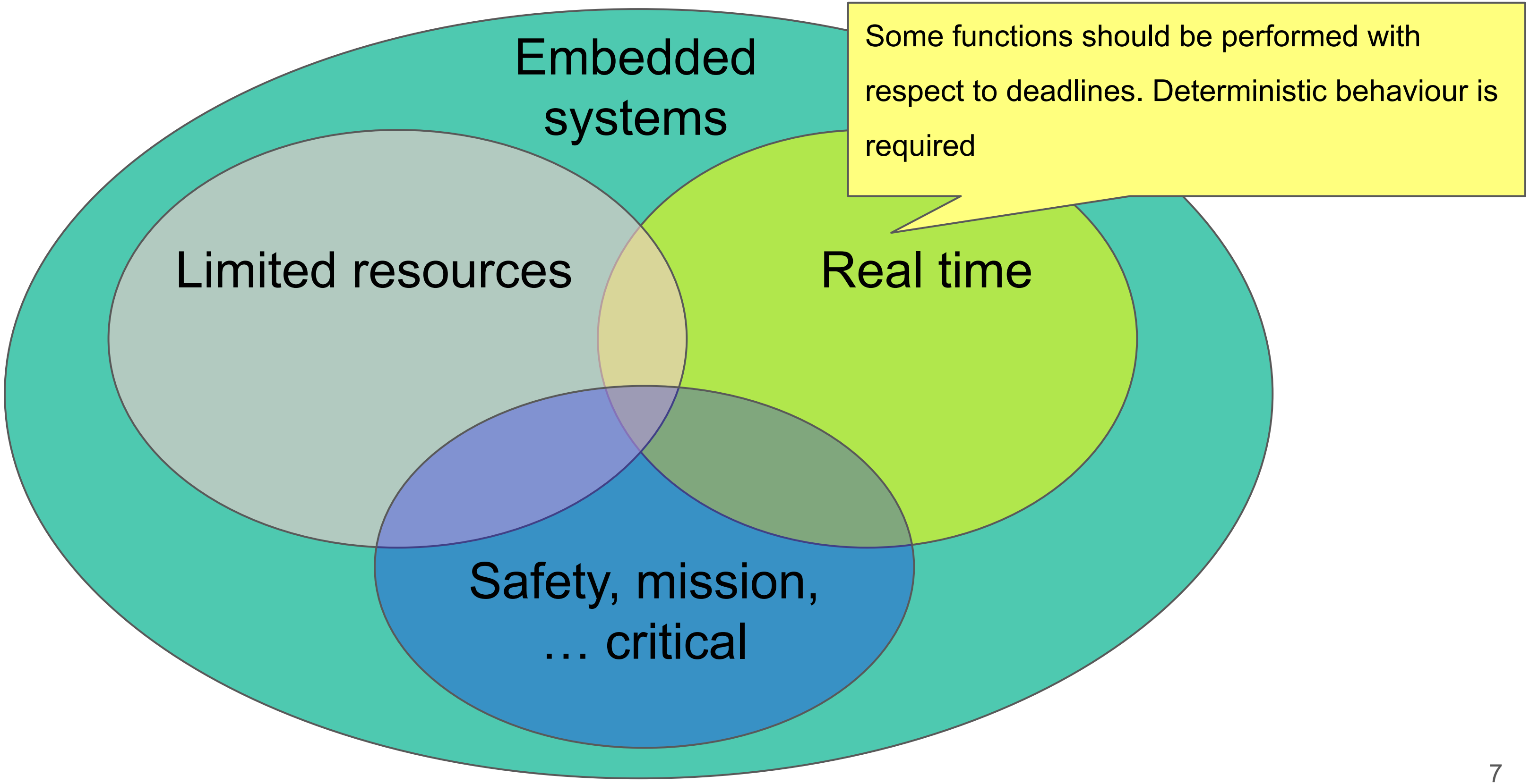

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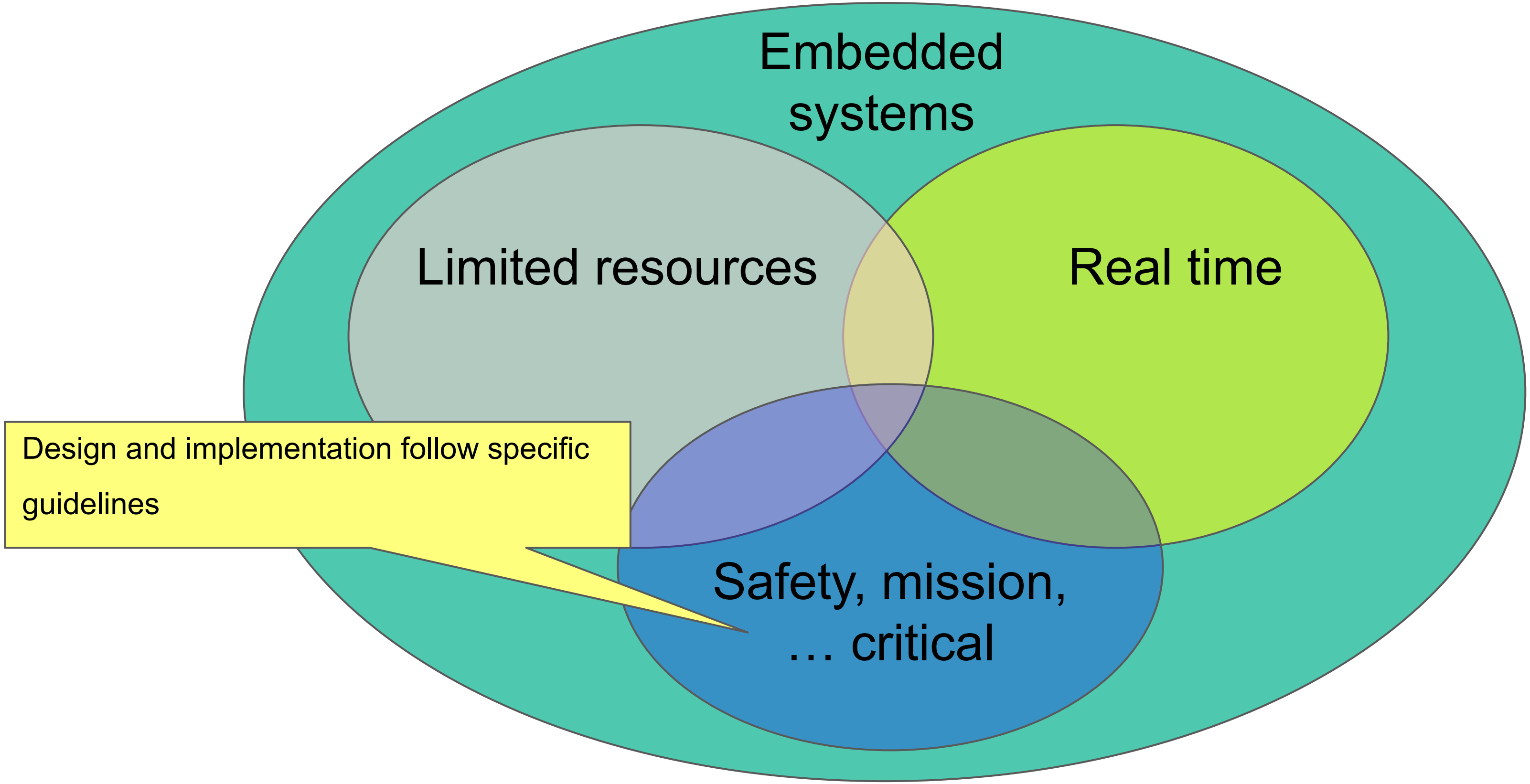

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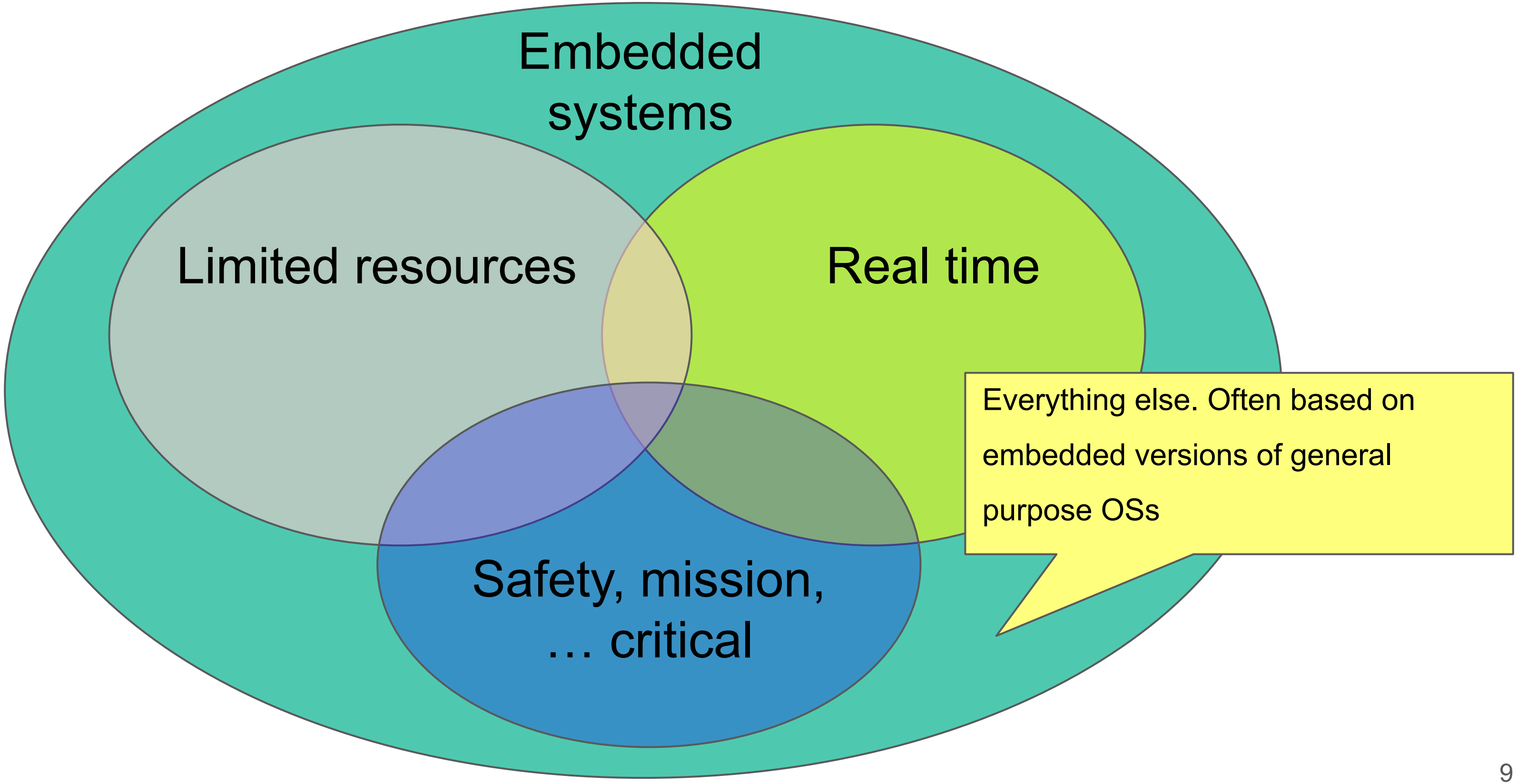


Embedded development characteristic

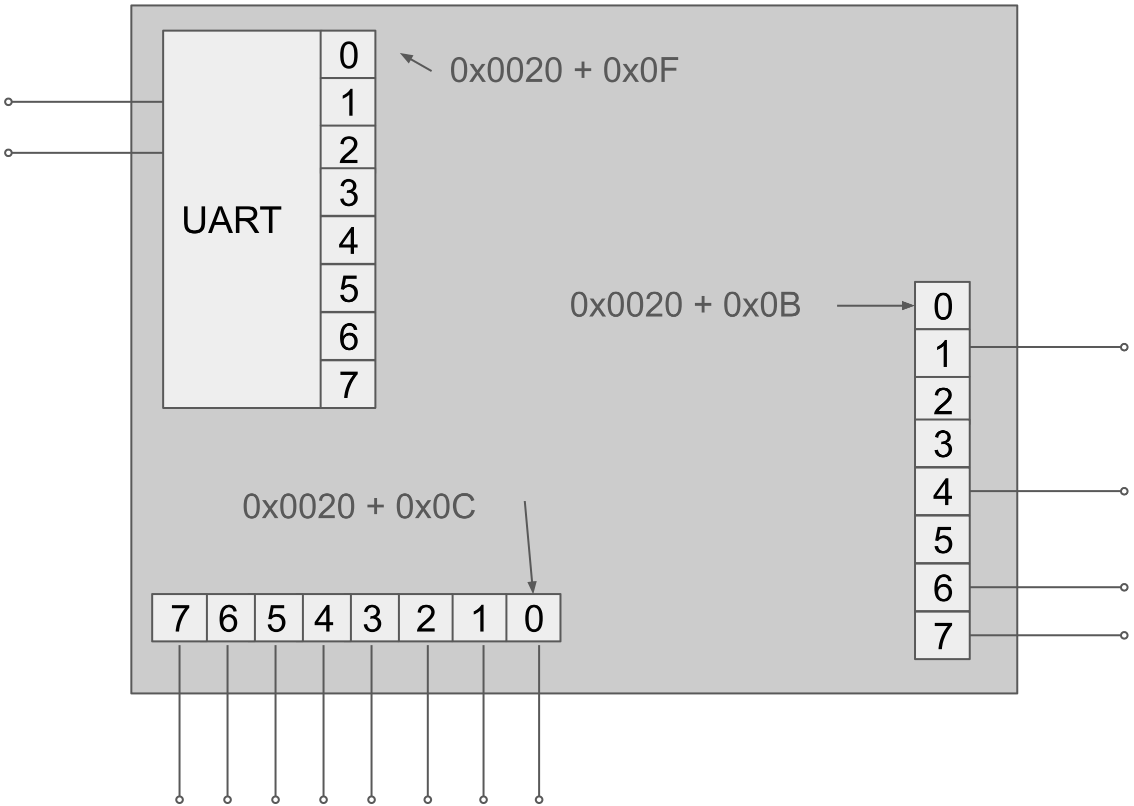
1. Software is deployed on target platform using specialized tooling
2. Diagnostics and debugging can be limited (software/hardware debuggers, disabled debugging, limited physical accessibility)
3. **Hardware can be unstable**
4. **Compilers might have defects**

Embedded development characteristic

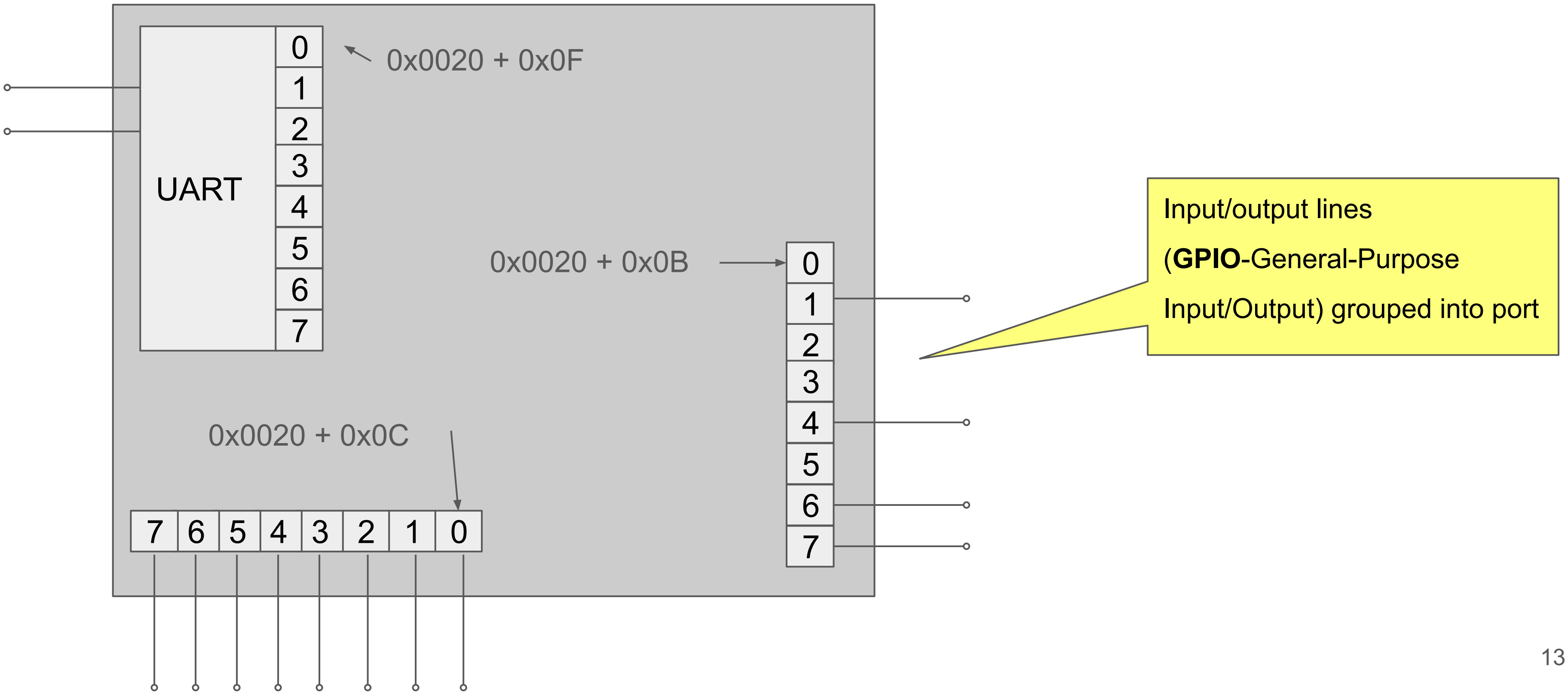
Code quality must be maximized prior to deployment:

- best practices (TDD, review, CI)
- primary testing on developer's machine (requires code portability)

Trivial hardware platform



Trivial hardware platform



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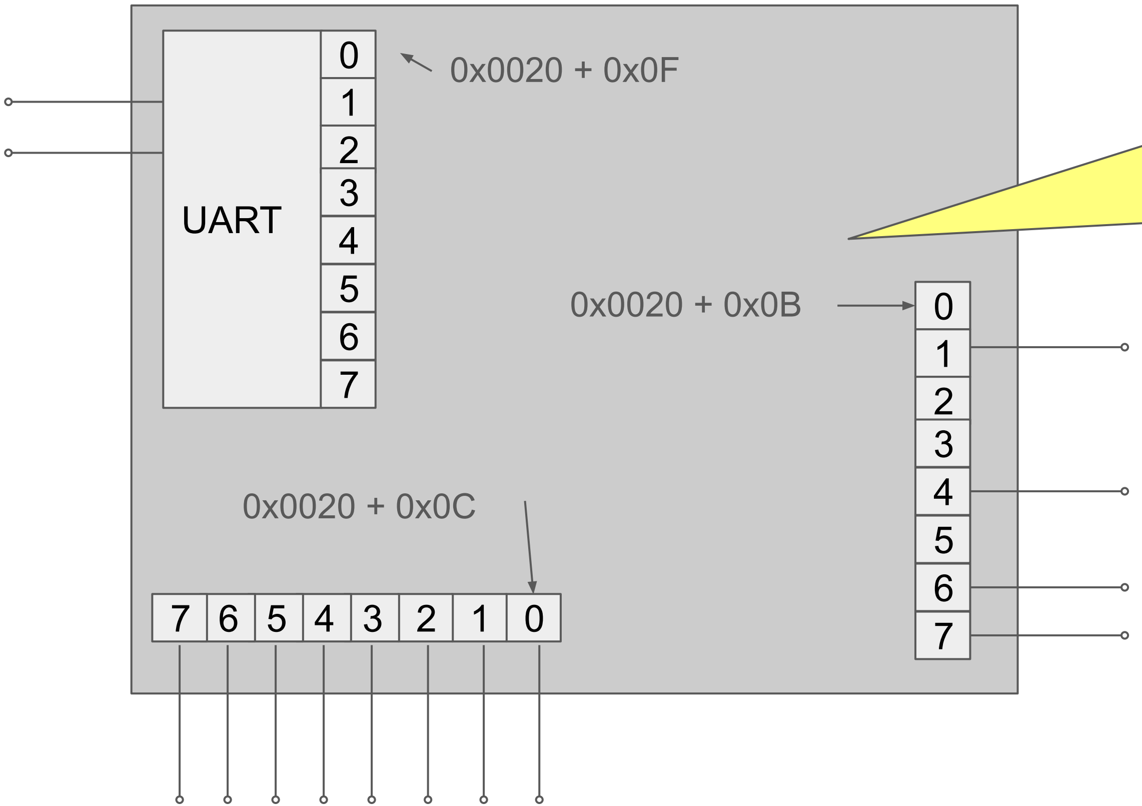
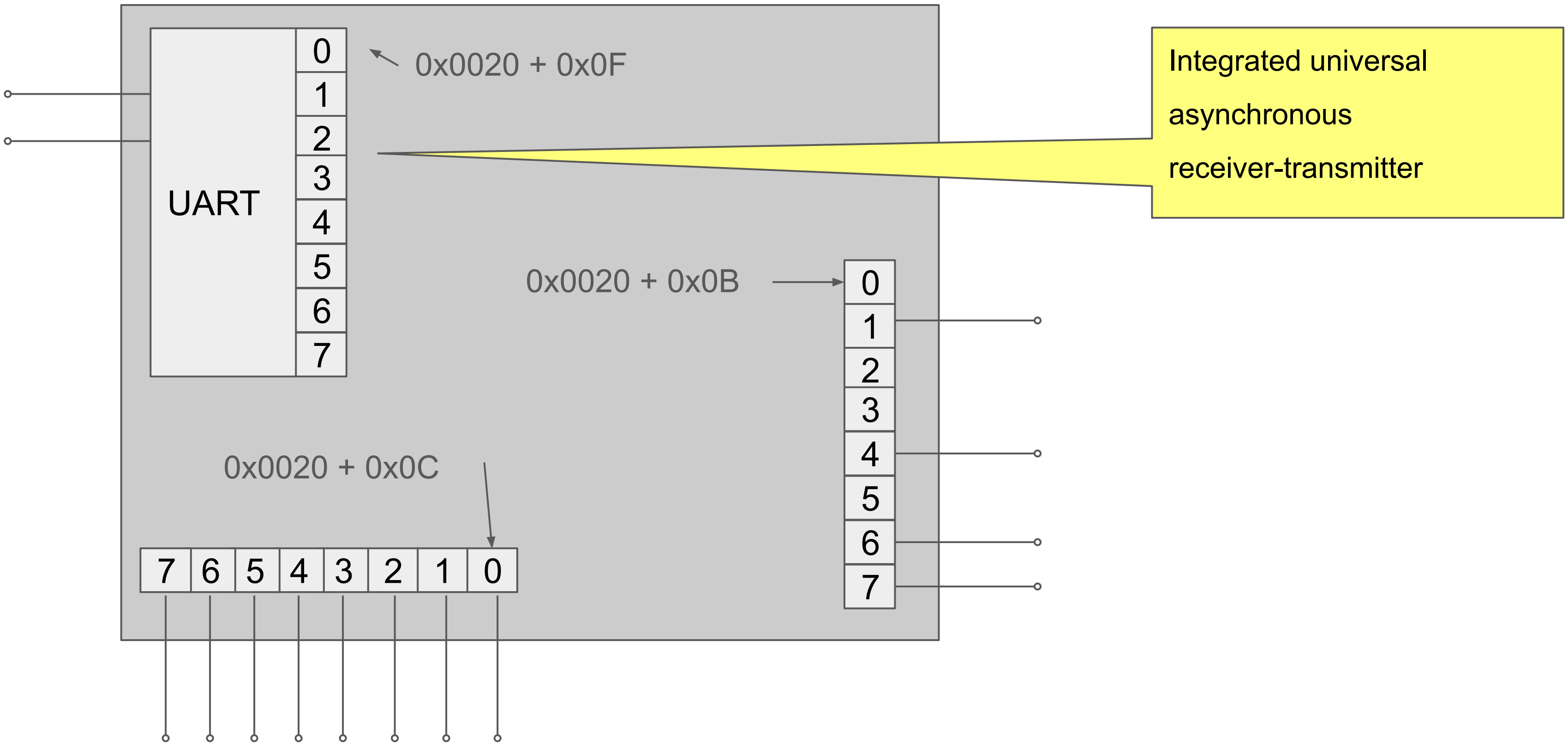


MMIO-Memory Mapped Input/Output

Line state is controlled via bit in a memory cell (**SFR**-Special Function Register)

Trivial hardware platform



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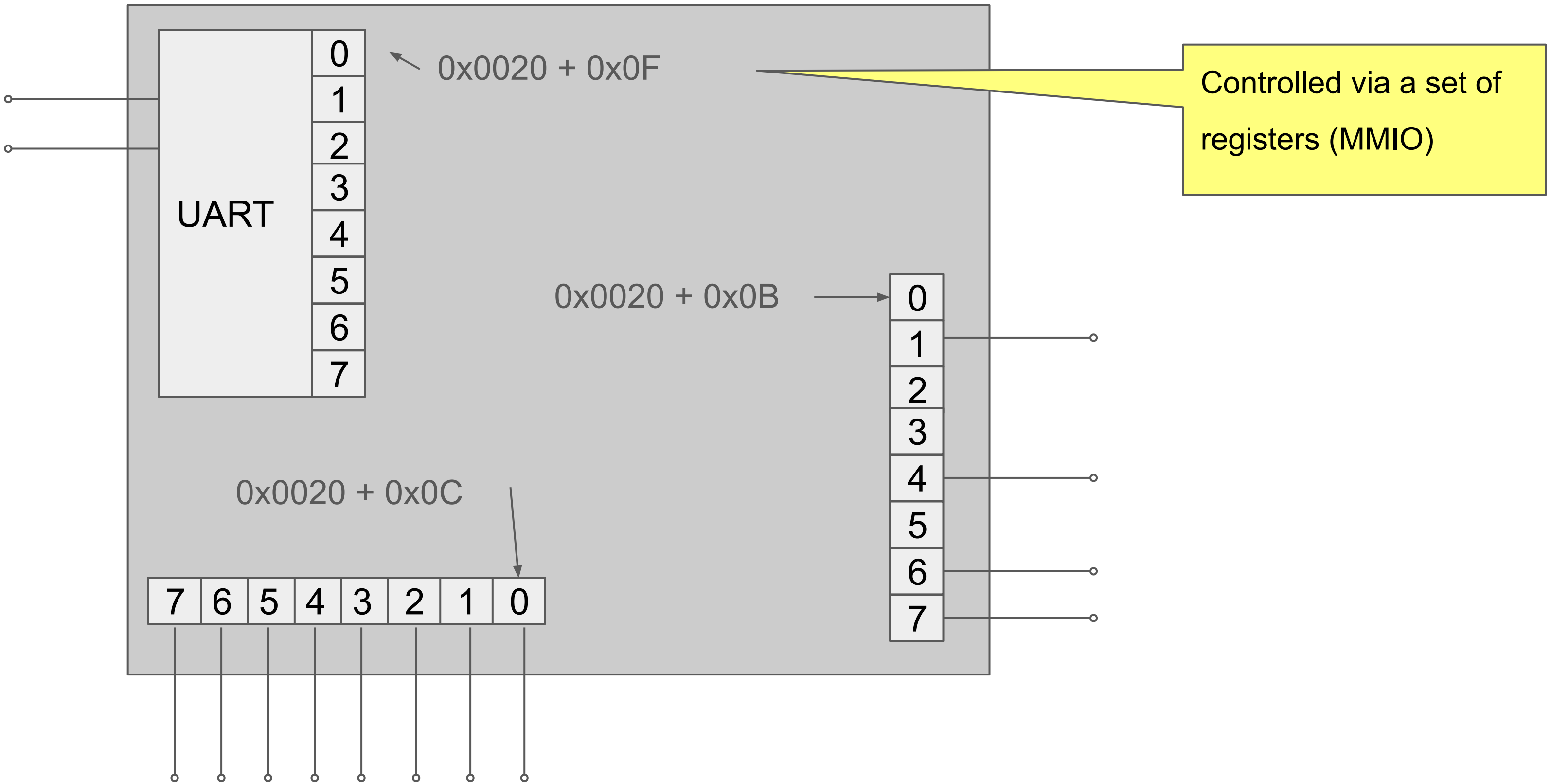
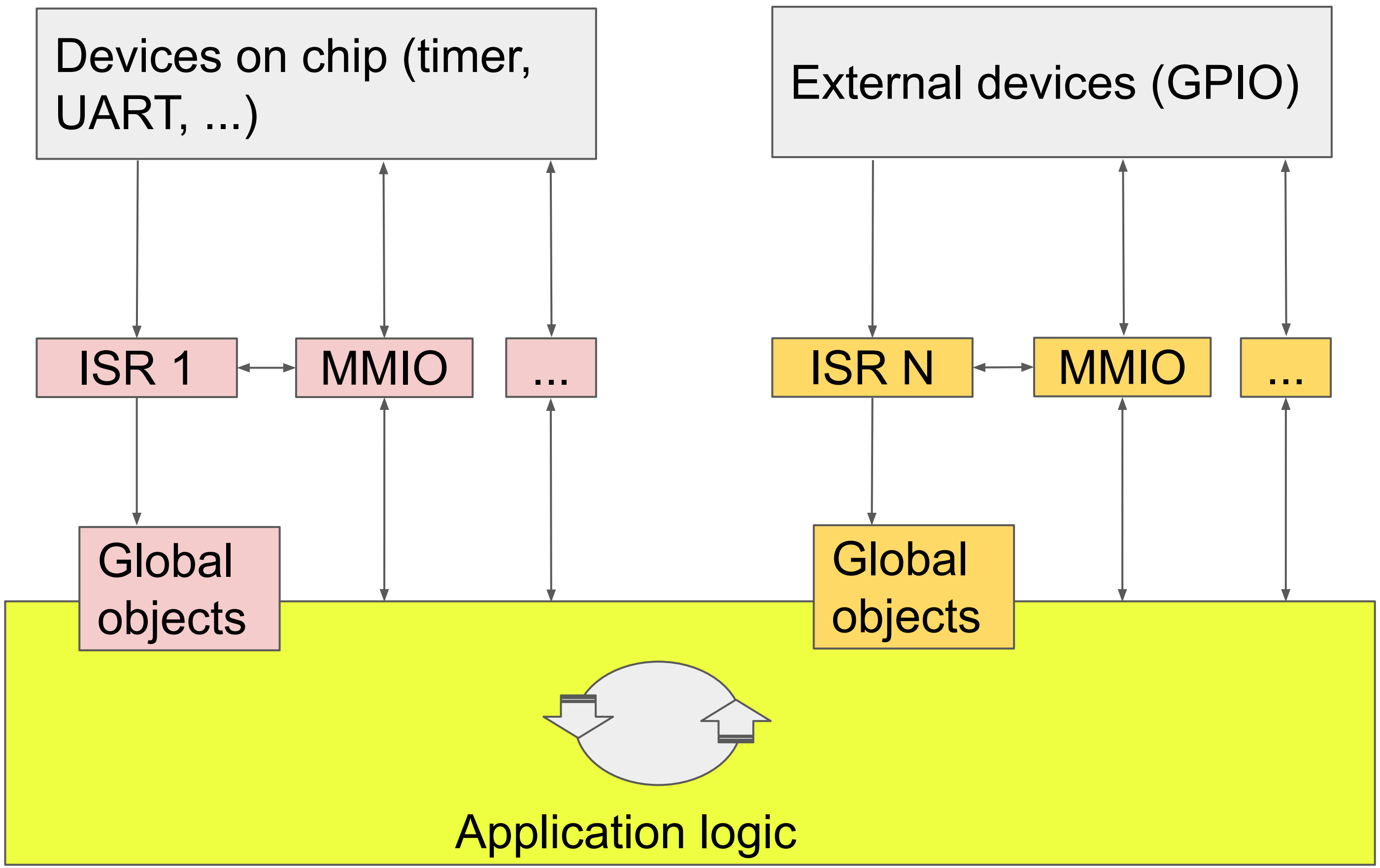


Trivial software architecture



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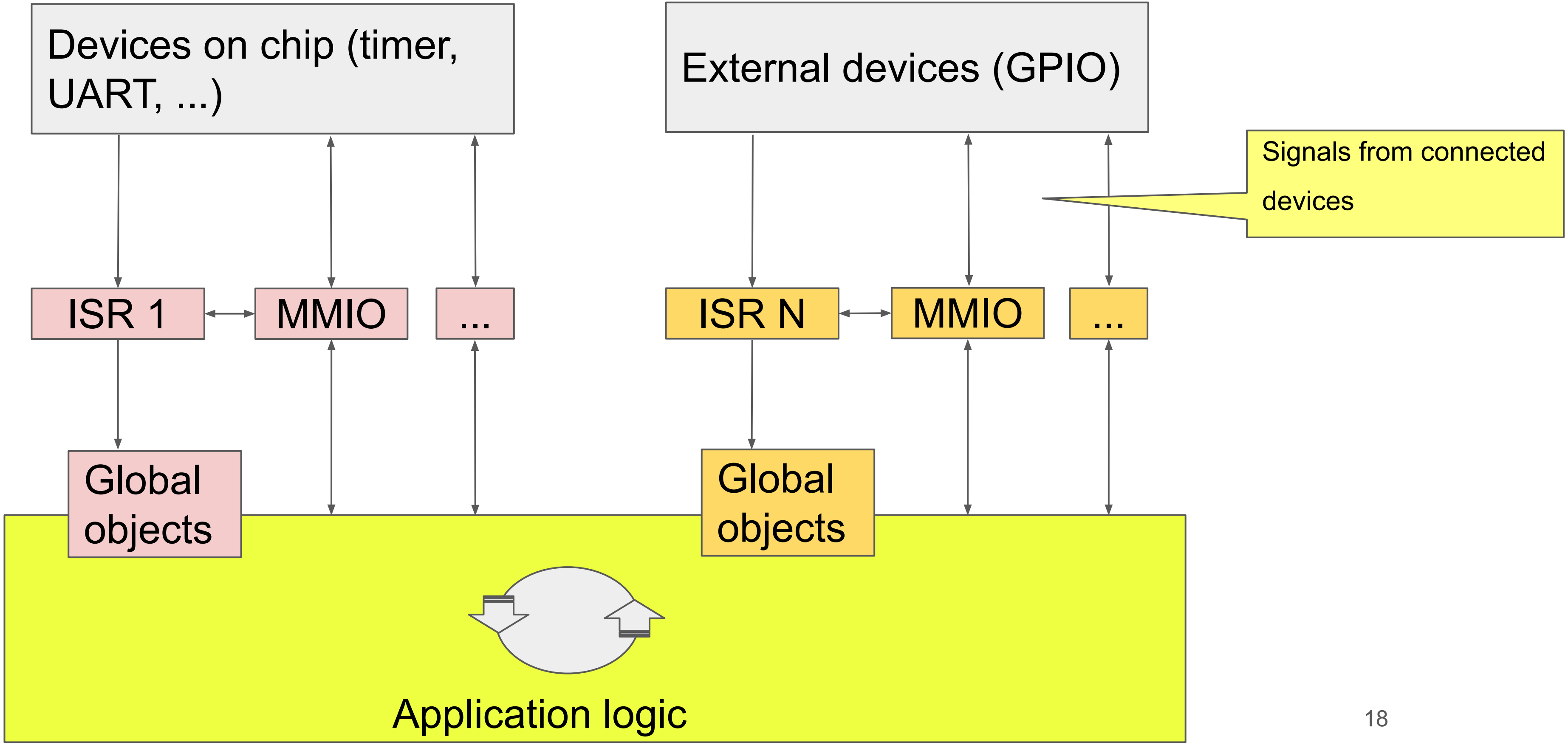

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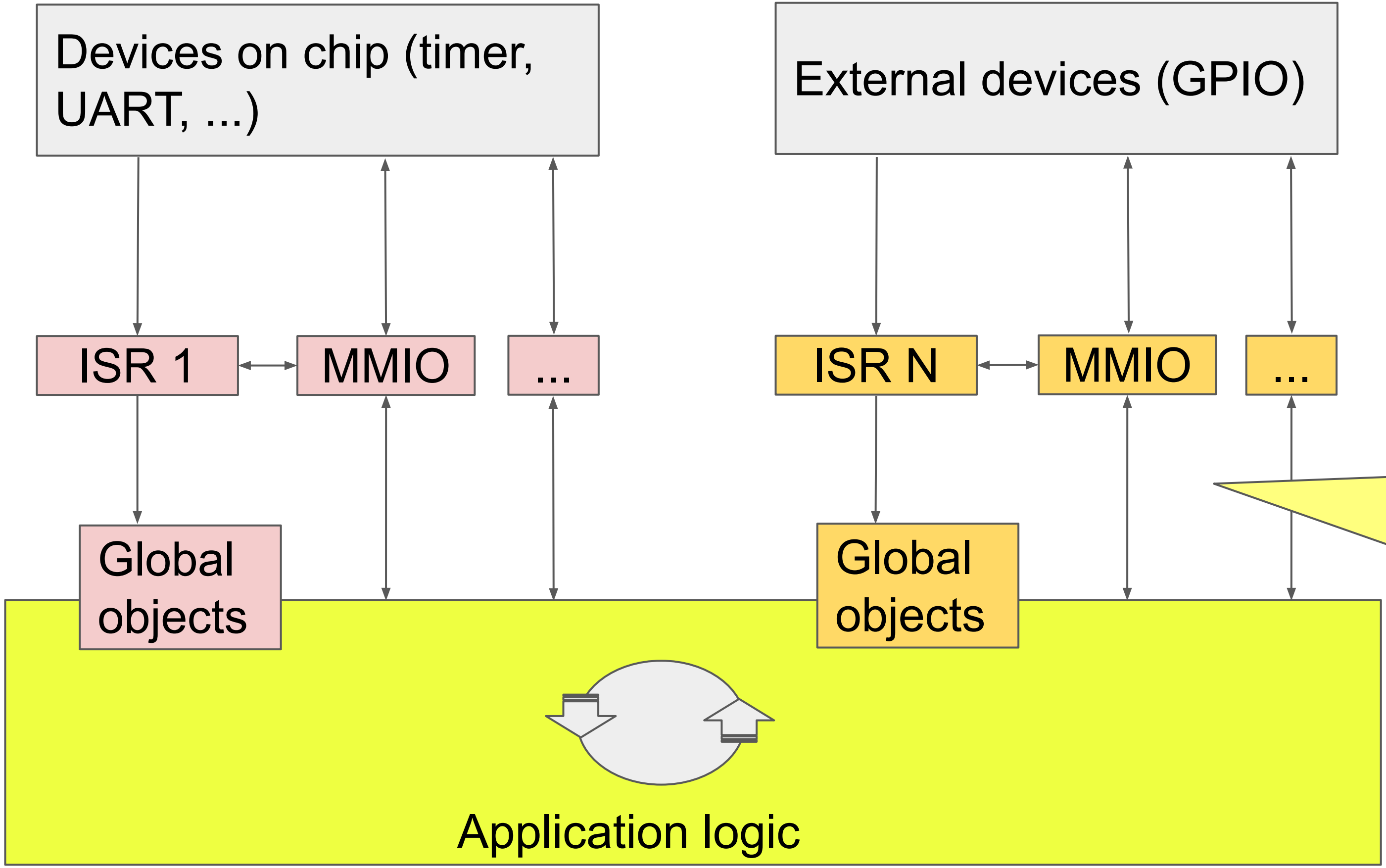
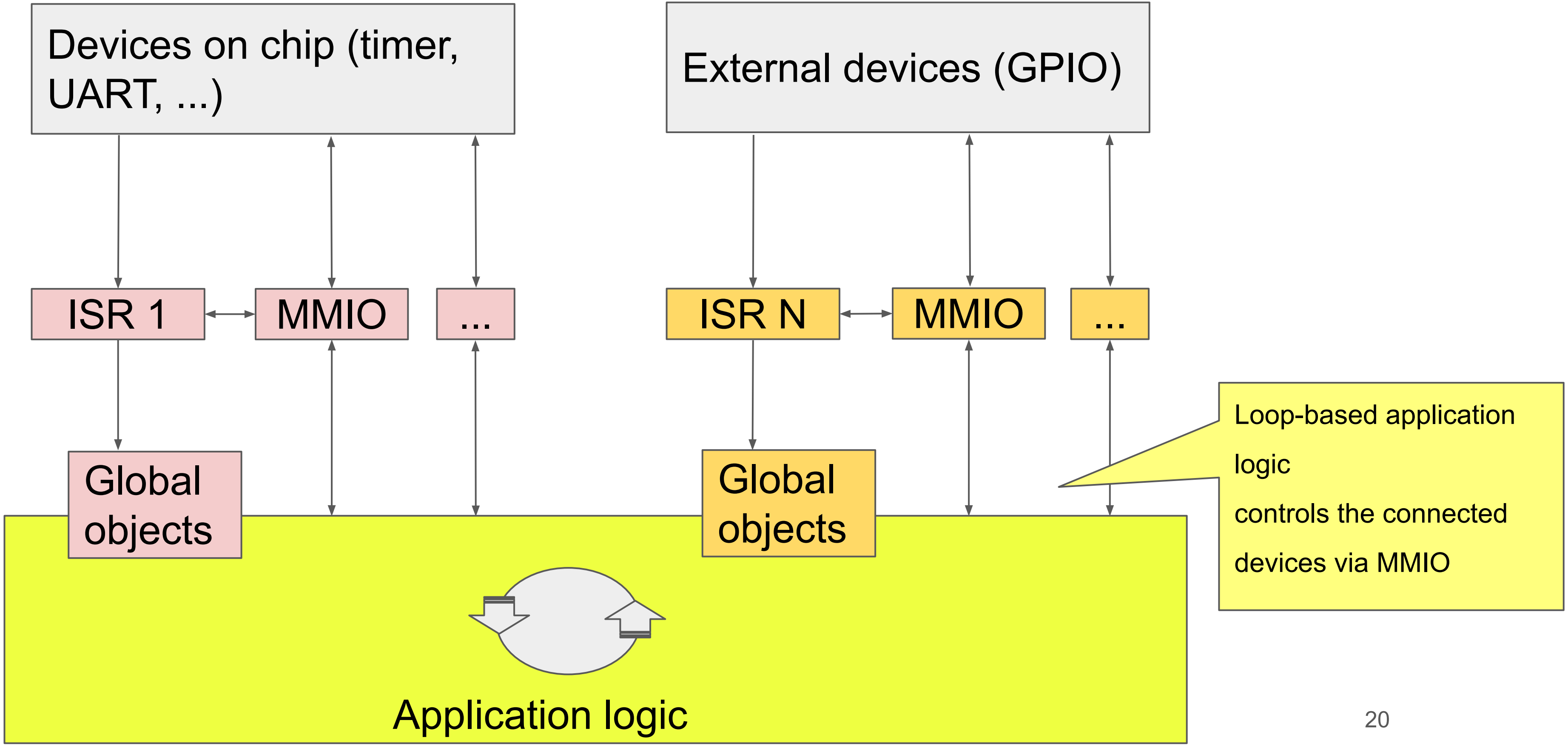
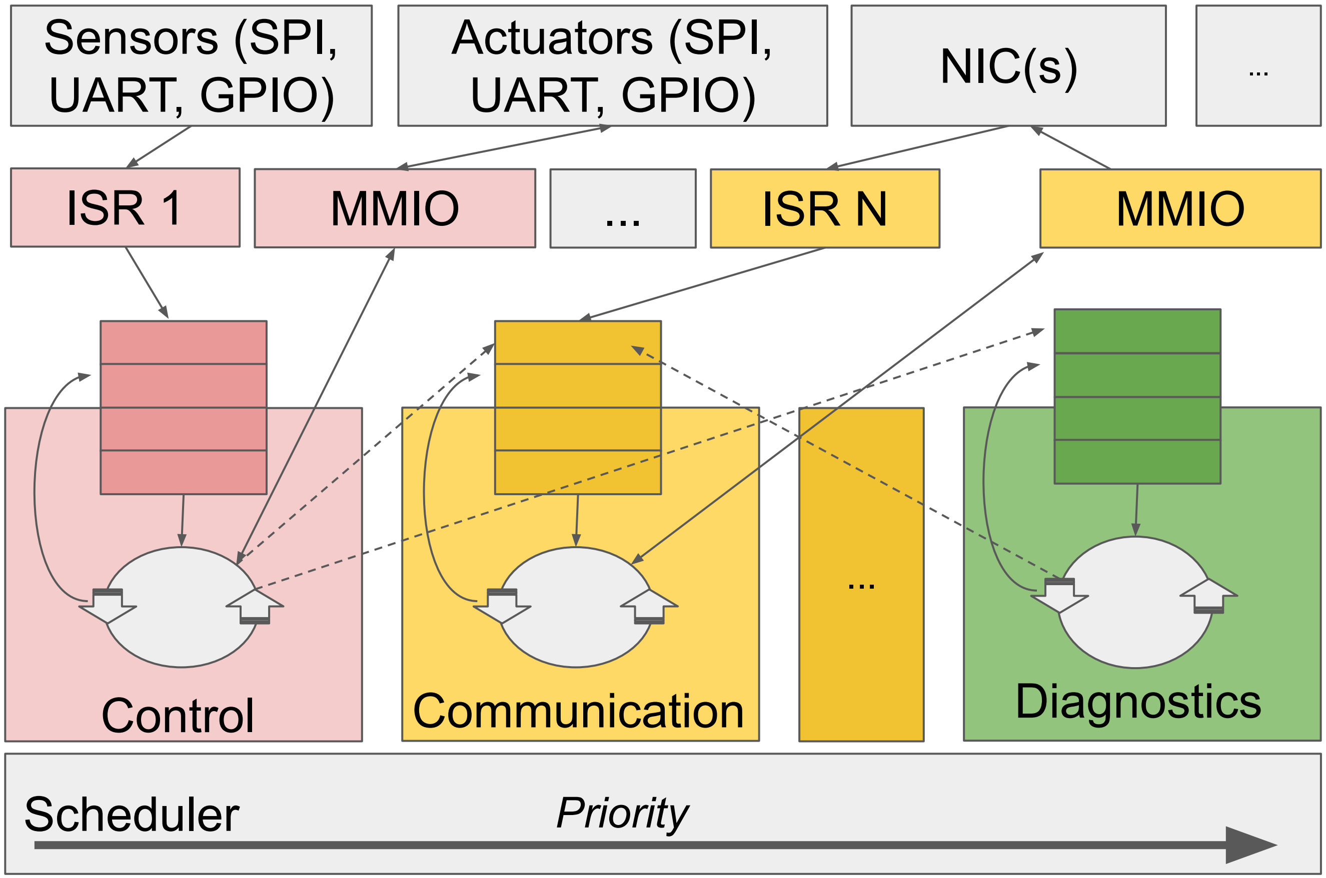


Signals from peripheral devices are delivered via **ISR** (Interrupt Service Routine) and **MMIO** polling

Trivial software architecture



Connected real time system architecture



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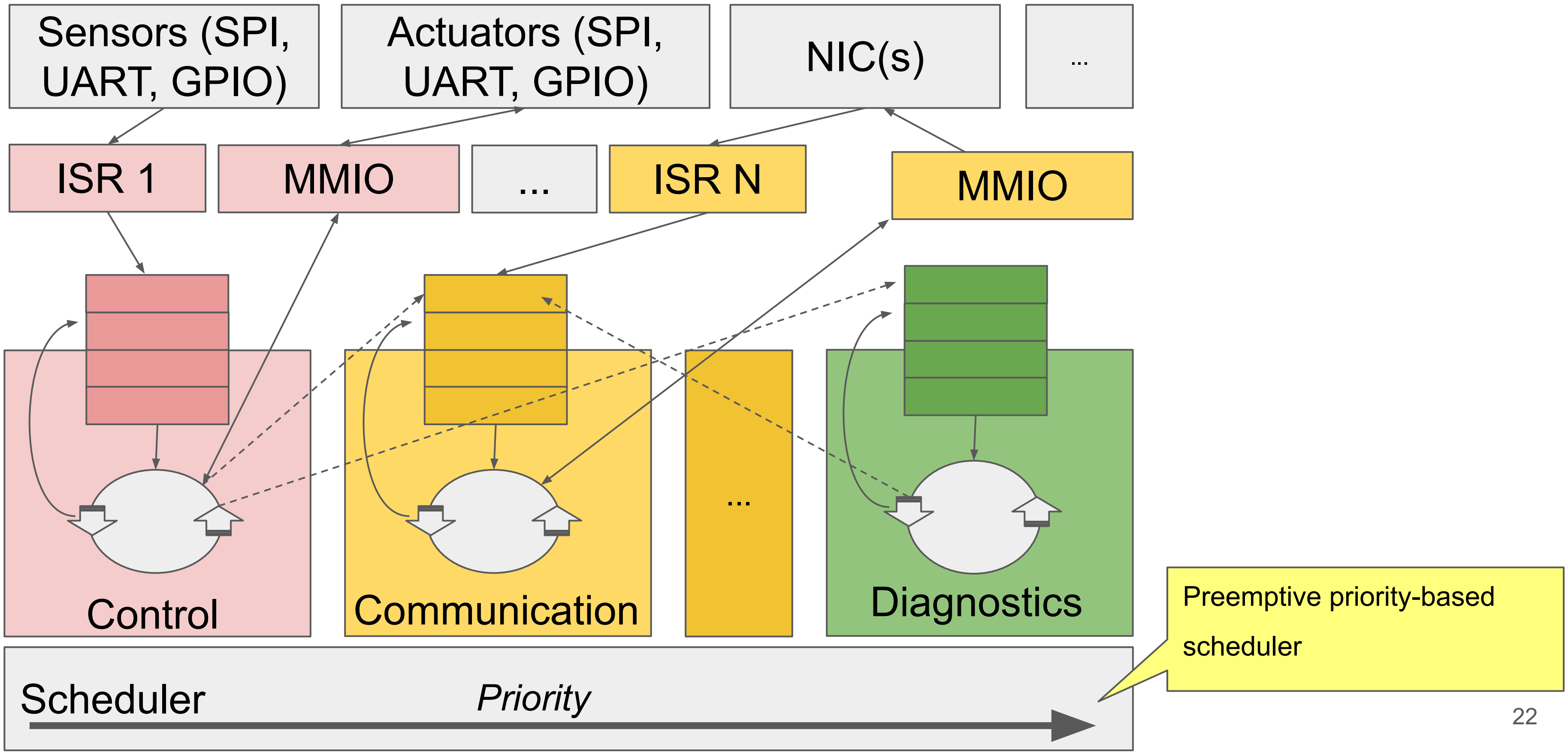
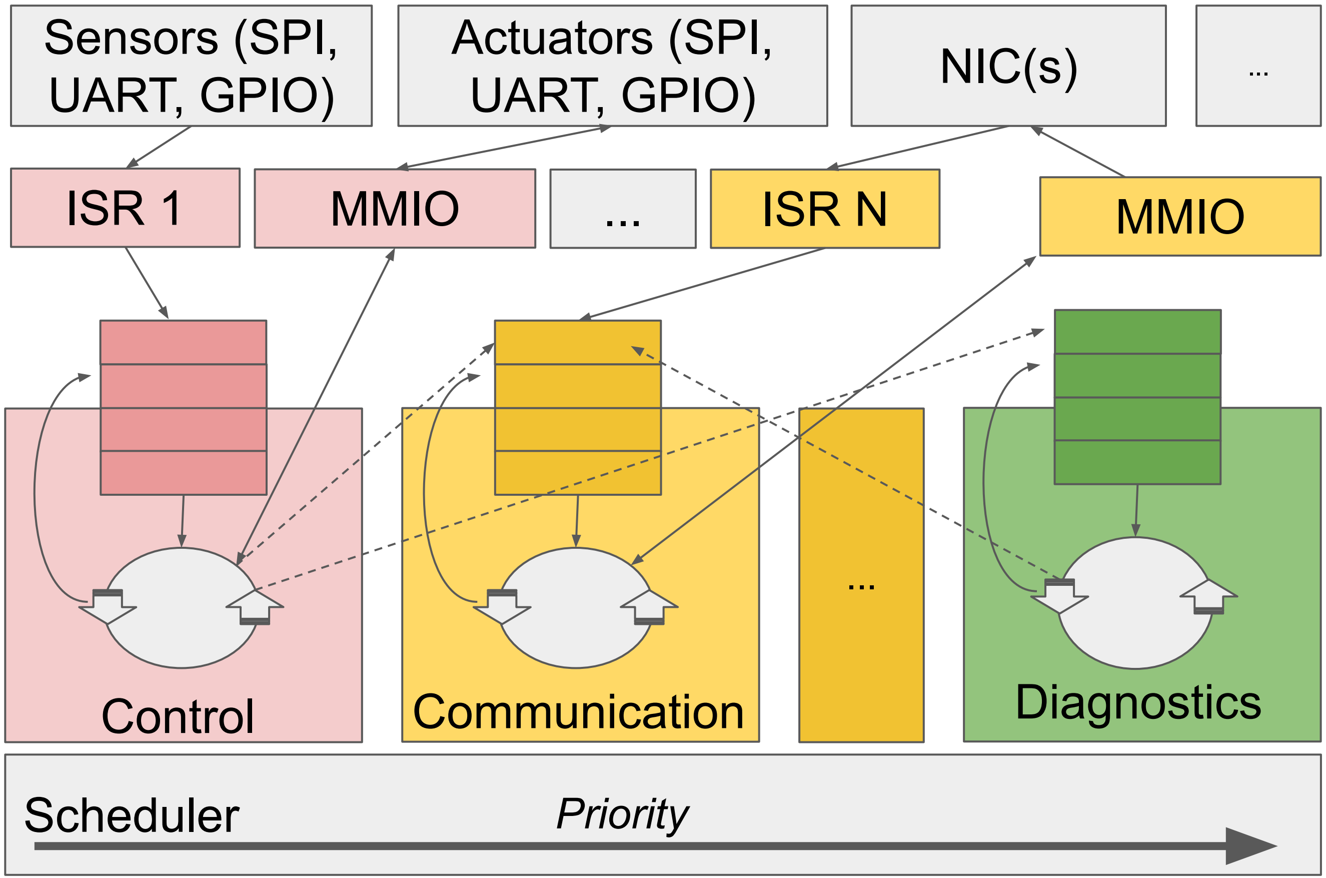
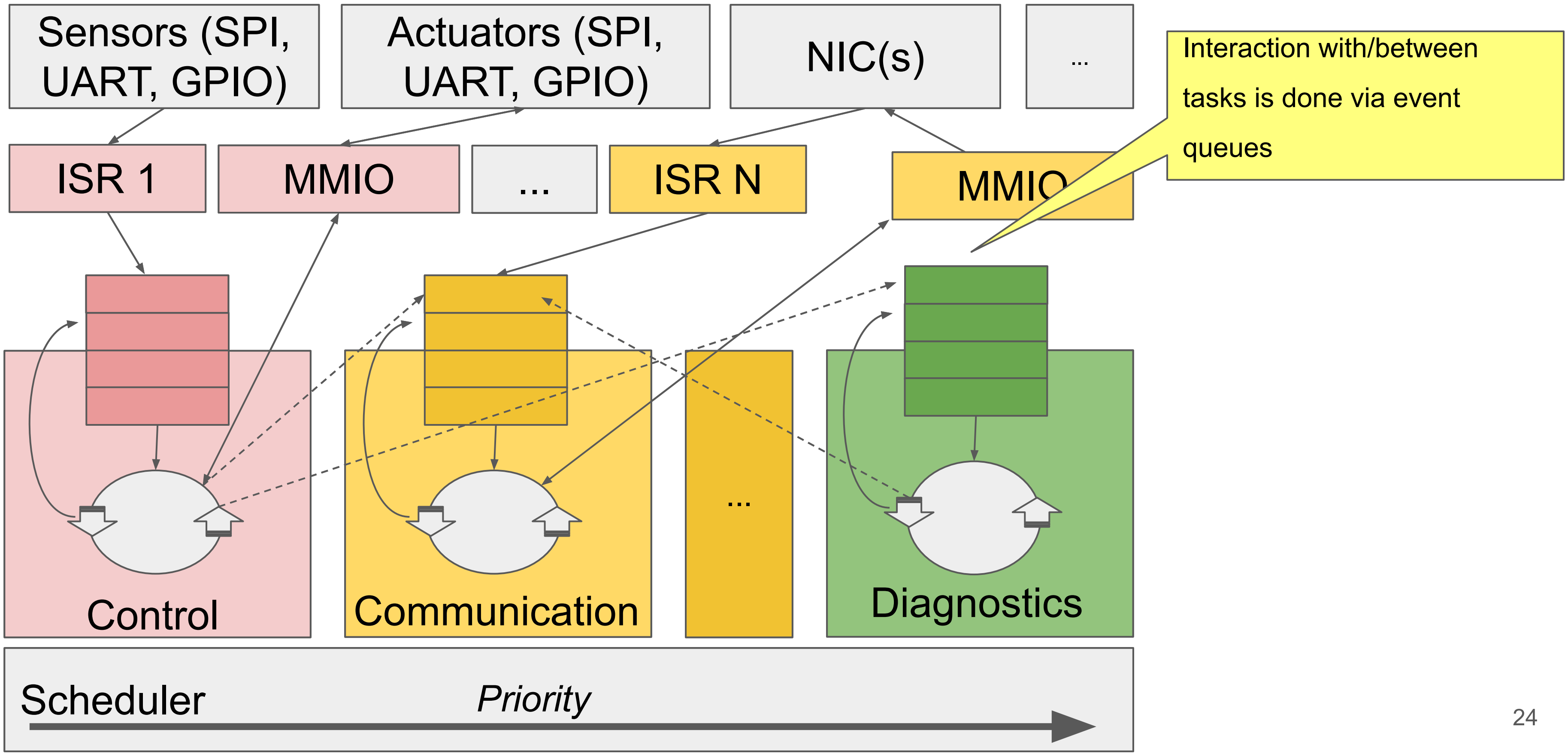


Connected real time system architecture



Tasks have static priorities and work exclusively with some set of resources (including memory and peripheral devices)

Connected real time system architecture



High performance non-embedded applications

- Task-based parallelism with dedicated narrow specialized tasks
- Async interaction via event queues
- Minimize resource contention
- Optimize memory usage

Embedded architectures and high-performance server/desktop architectures share characteristics

Programming language requirements

- Minimal overhead
- Portability
- Test-friendliness
- Availability of reusable frameworks for typical tasks

C++ satisfies the requirements

Limitations of C++ applicability

- Compiler support for a particular platform
- Availability of standard library components in a platform SDK
- Applicability of programming elements/constructs under platform or project constraints
- Industrial standards limitations

Compiler support of C++ **syntax** standards

GCC	C++20*, C++23*
Clang	C++20*, C++23*
SEGGER ARM Compiler	C++17*
IAR C++ Compiler	C++17*
Texas Instruments ARM Compiler	C++14*
Wind River Diab	C++14*

* - with limitations

Standard library: Hosted & Freestanding

- **Hosted**: contains components dependent on OS (filesystem, thread, ...).

  In practice *libc* for platform satisfies the dependencies on OS. “Real” OS is not required
- **Freestanding**: doesn’t contain OS specific components.

  Hardly usable - missing core elements (<utility> with *std::move* and *std::forward)*
- Some proprietary SDKs offer subset of standard library
- For some platforms standard library is not available

Limitations of C++ applicability

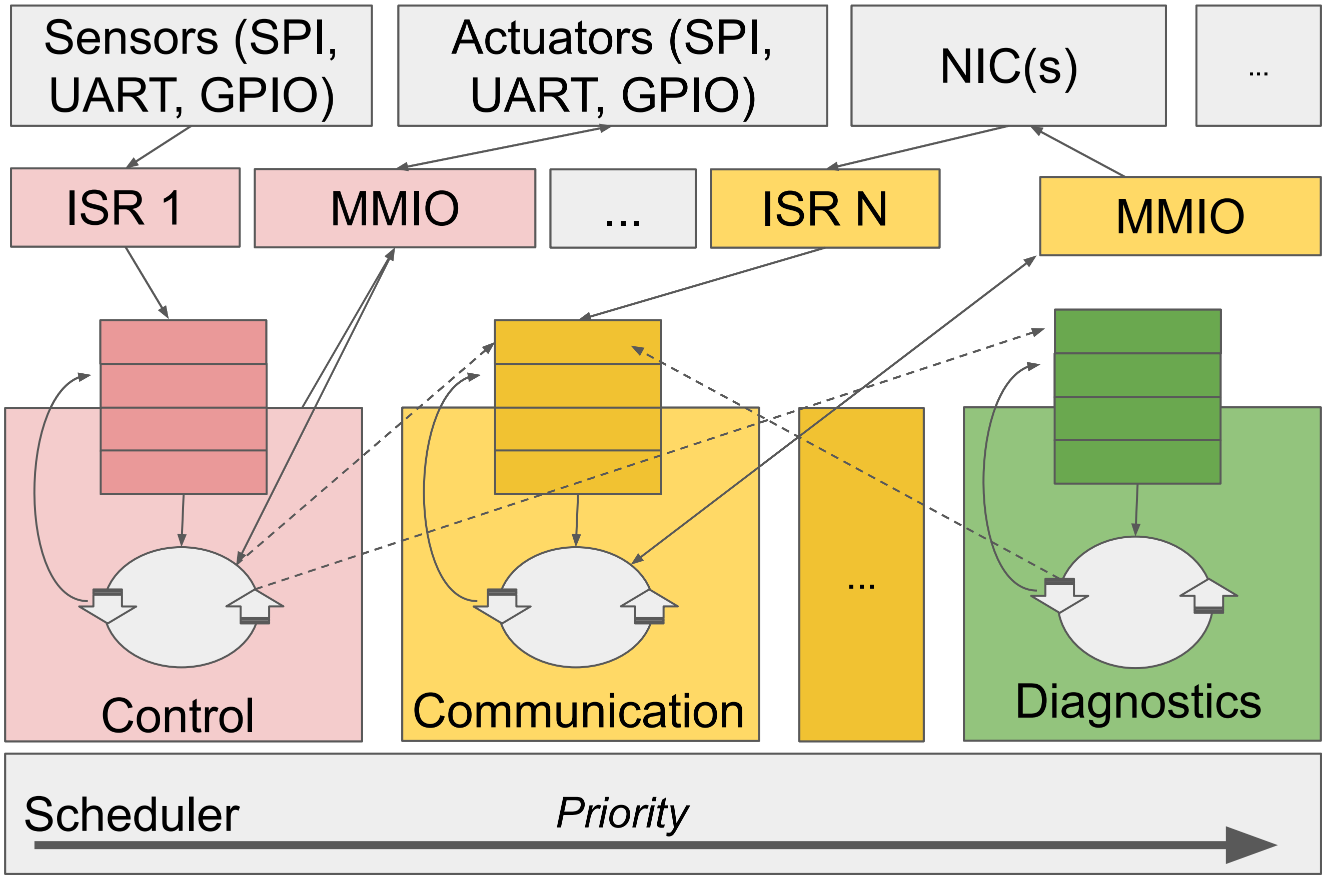
	Limited resources	Real time
Heap allocation	Maintenance overhead + fragmentation	Fragmentation + access synchronization => loss of determinizm
Exceptions	Increase of executable size	Analysis complexity, potential loss of determinism and low performance

Limitations of C++ applicability

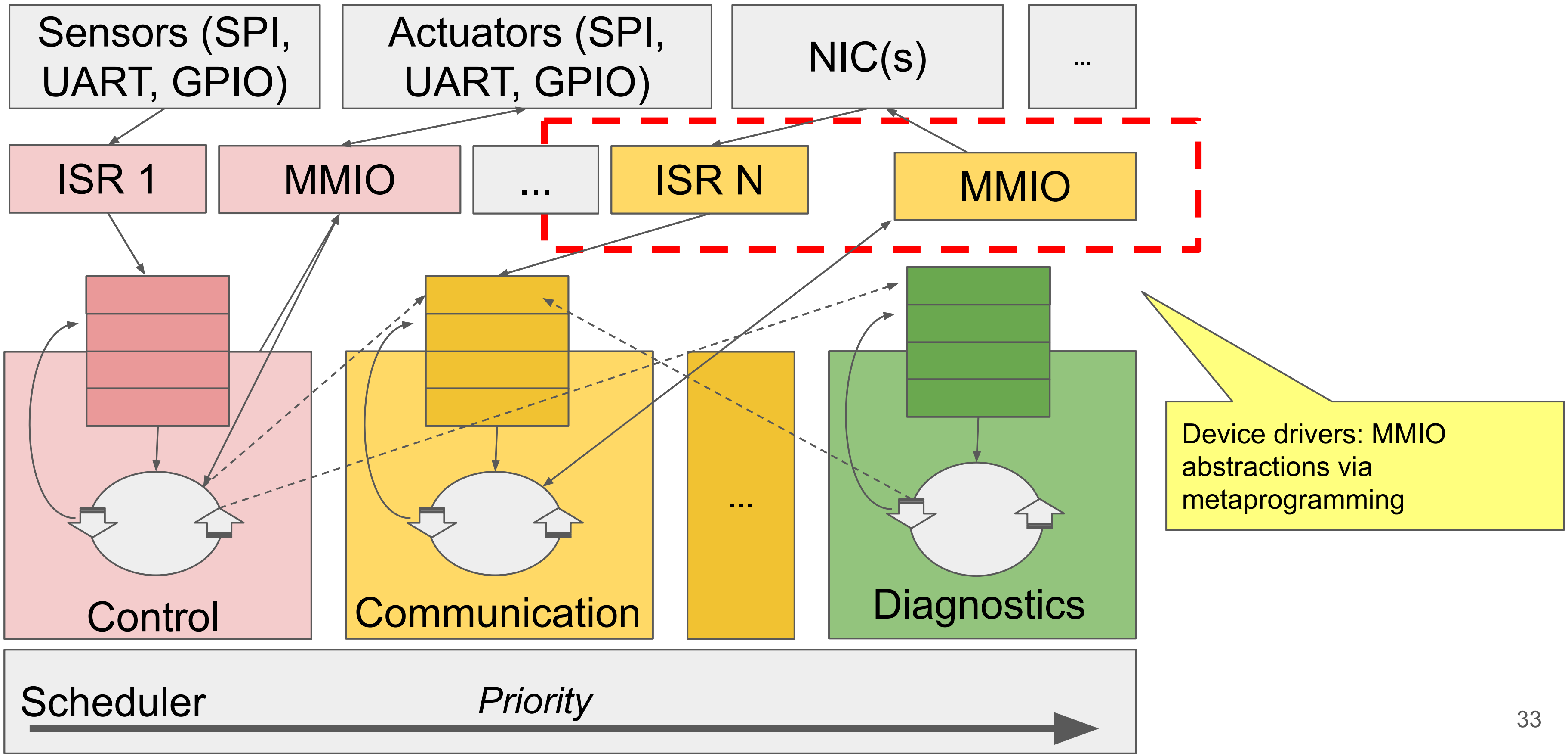
Industrial standards	JSF C++	MISRA C++	AUTOSAR C++ 14
Heap allocation	-+	-	-+
Exceptions	-	+	+

JSF C++ - Joint Strike Fighter Air Vehicle C++ (2005)
MISRA C++ - Motor Industry Software Reliability Association C++ (2008)
AUTOSAR C++14 - AUTomotive Open System ARchitecture C++14 (2017)

C++ application. Examples



C++ application. Examples



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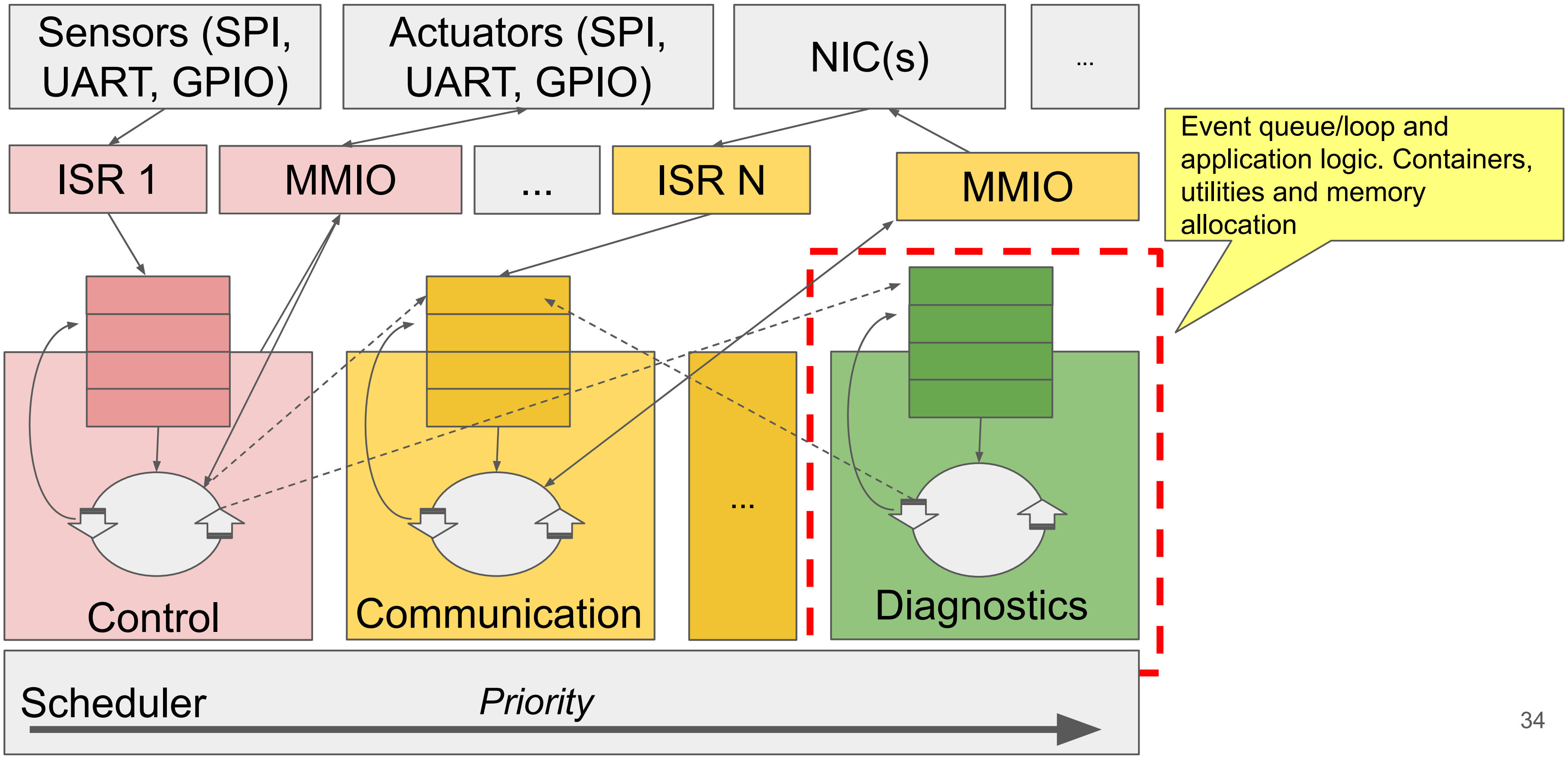
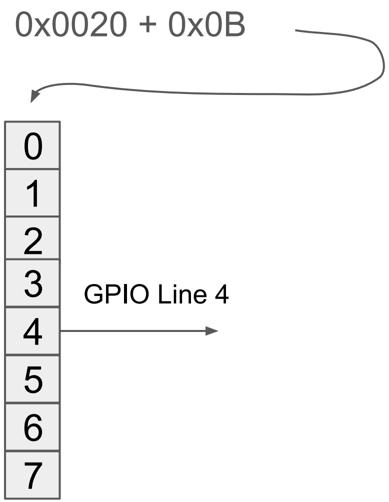


C++ for device driver development

MMIO register



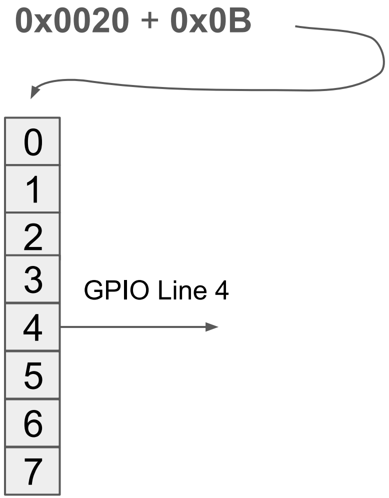

```
#define __SFR_OFFSET 0x20
#define _MMIO_BYTE(mem_addr) (*(volatile uint8_t *)(mem_addr))
#define _SFR_IO8(io_addr) _MMIO_BYTE((io_addr) + __SFR_OFFSET)
#define PORTD _SFR_IO8(0x0B)


#define _BV(bit) (1 << (bit))
#define PORTD4 4
#define PD4 PORTD4


PORTD |= _BV(PD4);
```

C++ for device driver development

MMIO register

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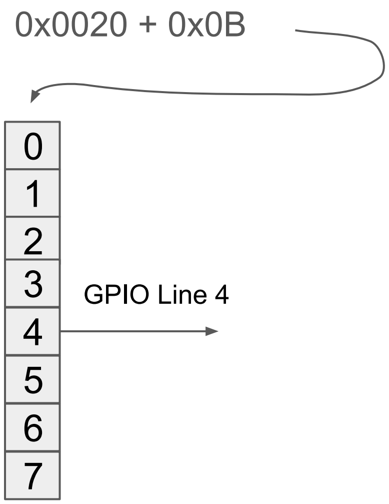
Address calculation

C++ for device driver development

MMIO register

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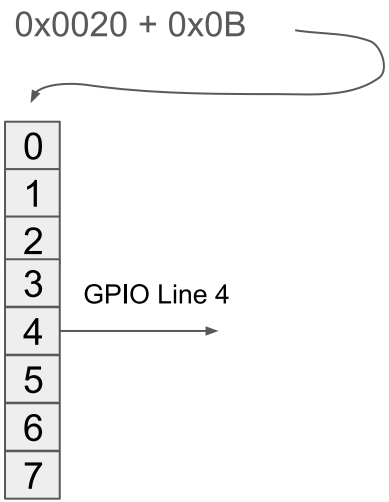
Mask calculation

C++ for device driver development

MMIO register

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PORTD |= _BV(PD4);
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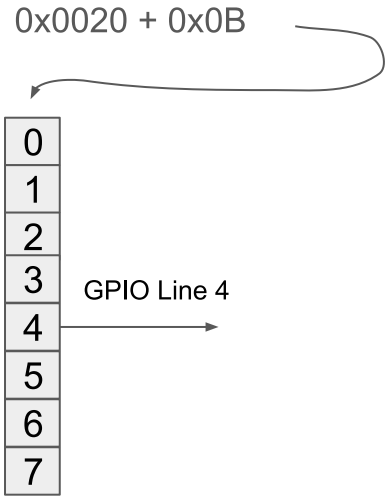
Setting the bit

C++ for device driver development

MMIO register



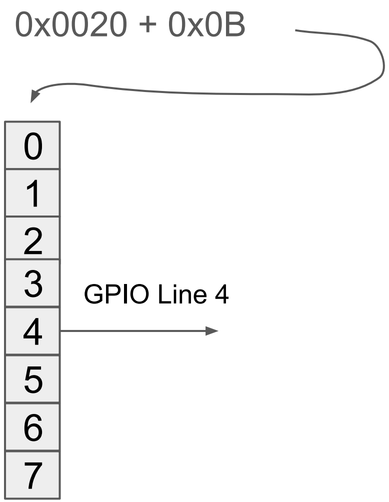
C-based implementation issues:

1. API code and code dependent on API can be executed only on target platform

2. No compile-time checks despite the fact that all register sizes and masks are known

C++ for device driver development

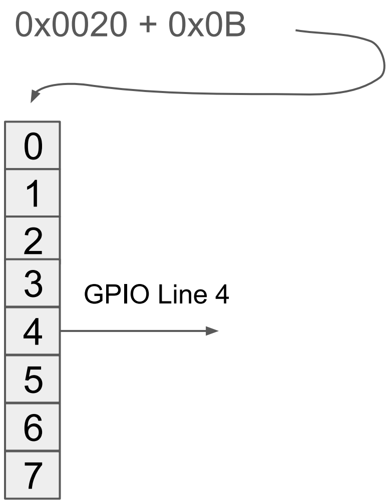
MMIO register




```cpp
template <typename T, uintptr_t Address,
                 uintptr_t Base>
struct address_with_base {
    using type = T;
    static T volatile *get_address() noexcept
    {
        return reinterpret_cast<T volatile*>
                    (Base + Address);
    }
};
```

C++ for device driver development

MMIO register

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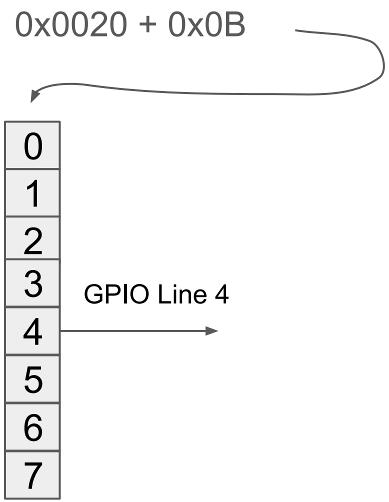
```

Referenced object type, base and offset

C++ for device driver development

MMIO register

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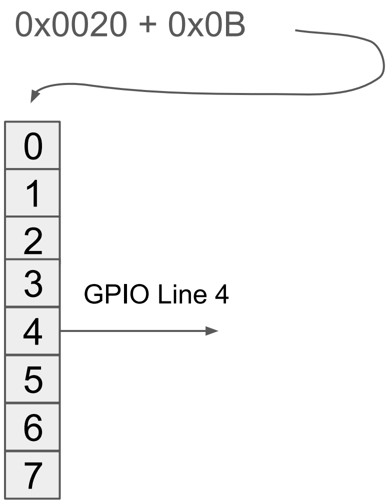
Address calculation

C++ for device driver development

MMIO register




```
template<typename T, uintptr_t Address>
using special_func_reg
    = mmio::address_with_base<T, Address, __SFR_OFFSET>;

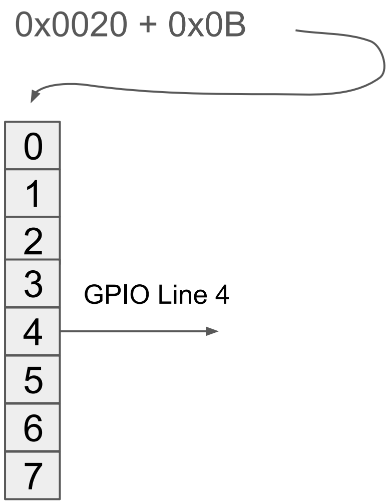
namespace ports::d {
using out
    = mmio::write_object<special_func_reg<uint8_t, 0x0B>, 0, 8>;
//...
}



ports::d::out::bits<4> pin;
pin.set();
```

C++ for device driver development

MMIO register

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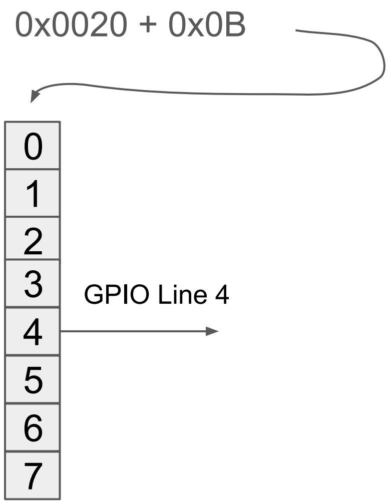
Alias for concrete architecture

C++ for device driver development

MMIO register

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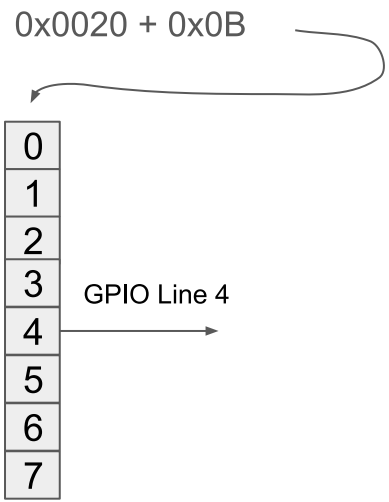
Concrete register description

C++ for device driver development

MMIO register

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//...
}


ports::d::out::bits<4> pin;
pin.set();
```

Mask instantiation (4th bit can be accessed)

C++ MMIO abstractions. Checks

```
template <typename Location, uint8_t Offset, uint8_t Length = 1>
struct write_object {
    using Type = typename Location::type;
    template <uint8_t... bit_offsets>
    using bits = bits_write_object<
        std::enable_if_t<detail::check_bounds<Type, bit_offsets...>(
            Offset, Length), Location>,
        Offset,
        Length,
        bit_offsets...>;
```

Compile-time check of the register boundaries

C++ MMIO abstractions. Optimizations

```
void set()
{
    if constexpr (detail::does_cover_the_whole_object<Type>(Offset, Length)) {
        *Location::get_address() = mask;
    } else {
        constexpr typename Location::type valueMask
            = detail::generate_mask<typename Location::type>(Offset, Length);
        *Location::get_address() &= (valueMask | (mask << Offset));
    }
}
```

Load/Store optimization

C++ MMIO abstractions. Address abstraction

```
template <typename T, uintptr_t Address,
                  uintptr_t Base>
struct address_with_base {
    using type = T;
    static T volatile *get_address() noexcept
    {
        return reinterpret_cast<T volatile*>
                    (Base + Address);
    }
};
```

```
template <typename T,
                  T *Address>
struct mock_address
{
    using type = T;
    static T *get_address() noexcept
    {
        return Address;
    }
};
```

C++ MMIO abstractions. Testing

```
static uint8_t object = 0;

TEST(mmio, WrapperCoversTheWholeObjectAndObjectIsZero_SetValue_TheObjectHasNewValue)

{

    using test_register = mmio::write_object<mock_address<uint8_t, &object>, 0, 4>;

    test_register::bits<0, 1, 3> register_bits;

    register_bits.set();

    EXPECT_EQ(object, 0b1011);

}
```

Mock, providing the address of a static object

C++ MMIO abstractions

1. The layout for the platform, based on developed abstractions, can be generated from SDK C-code or specification files
2. Classes representing MMIO can be used to implement more complex pieces, e.g. drivers

Device drivers. Dependency injection

<table>
<tr><td>Callbacks (C-style function pointers or functional objects)</td><td rowspan="2">1. Extra code and indirection might be unacceptable for performance critical areas
2. Dependency on compiler ability to optimize a call (devirtualization, LTO)</td></tr>
<tr><td>Run-time polymorphism</td></tr>
<tr><td>Compile-time polymorphism</td><td>1. No virtual call (no indirection)
2. No need to introduce hierarchies where they are not needed</td></tr>
</table>

Device driver. Testing

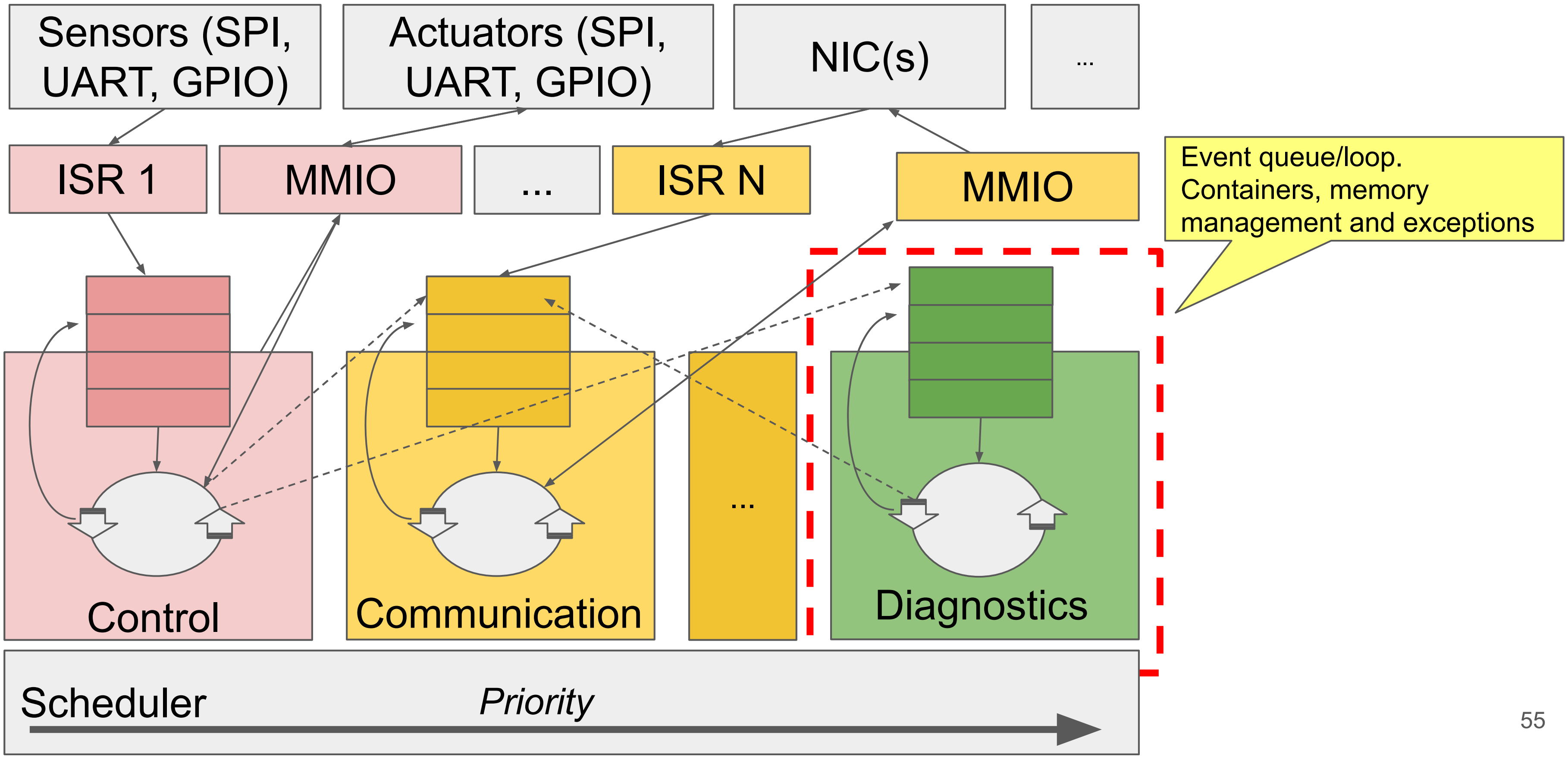
```
template <typename TxInterruptControllBit, typename RxTxRegisters>
struct uart_control {...};

TEST(uart_control, enable_tx_interrupt_bit_is_set)
{
    StrictMock<MockBit> tx_intr_control_bit;
    //...
    EXPECT_CALL(tx_intr_control_bit, set());
     //...
    drivers::uart::uart_control uart_control{tx_intr_control_bit, rxtx};

    uart_control.enable_tx_interrupt();
}
```

```
struct MockBit {
    MOCK_METHOD0(set, void());
    MOCK_METHOD0(unset, void());
};
```

C++ for device drivers development. Summary

1. Testable and portable code can be developed based on template metaprogramming and compile-time polymorphism
2. MMIO abstraction idea is not novel (Kvasir). But no “standard/default” framework
3. Considering new language features, the topic can be interesting for metaprogramming “gurus”

C++ application. Examples



Reusable event queue/loop

```
using task_event_loop = event_loop<...>;
task_event_loop loop;

void task_worker()
{
    loop.run();
}

void some_function(task_event_loop &loop)
{
    loop.schedule(some_timeout, [](){ gpio_led.set(); });
}
```

Reusable event queue/loop

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Configurable generic event loop class

Reusable event queue/loop

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}
```

Loop is executed in the task main function

Reusable event queue/loop

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}
```

Clients can schedule arbitrary work

Memory allocation

Option without heap-allocation:

- objects with automatic or static storage duration
- objects (containers) with embedded static storage
- custom allocation (custom allocator, new/delete overloading)
- pool allocation
- intrusive containers

Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	By standard*	Part of Hosted
Boost*	Not used*	Configurable*	Hosted*
EASTL*	Not used*	Configurable	None
ETL	Not used	Configurable	None

1. STL - Standard Template Library
2. Boost (https://github.com/boostorg/boost)
3. EASTL - Electronic Arts Standard Template Library (https://github.com/electronicarts/EASTL)
4. ETL - Embedded Template Library (https://github.com/ETLCPP/etl)

Containers, algorithms and utilities

Framework	Heap allocation	Ex	ency on std
STL, Utility lib	**By standard***	By	Hosted
Boost*	Not used*	Co	
EASTL*	Not used*	Configurable	None
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For STL containers custom allocators can be provided.

For some components in Utility lib that is not possible (`std::function`)

1. STL - Standard Template Library
2. Boost (https://github.com/boostorg/boost)
3. EASTL - Electronic Arts Standard Template Library (https://github.com/electronicarts/EASTL)
4. ETL - Embedded Template Library (https://github.com/ETLCPP/etl)

Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	td
STL, Utility lib	By standard*	**By standard***	
Boost*	Not used*	Configurable*	
EASTL*	Not used*	Configurable	None
ETL	Not used	Configurable	None

No standard customization for handling exceptional situations. Typically `std::abort` is called instead of throwing

1. STL - Standard Template Library
2. Boost (https://github.com/boostorg/boost)
3. EASTL - Electronic Arts Standard Template Library (https://github.com/electronicarts/EASTL)
4. ETL - Embedded Template Library (https://github.com/ETLCPP/etl)

Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	[illegible]	[illegible] of Hosted
Boost*	**Not used***	[illegible]	[illegible]ted*
EASTL*	Not used*	[illegible]	[illegible]e
ETL	Not used	Configurable	None

Components of `container` and `intrusive` libs can be used without heap.

Components of `pool` can be used to facilitate custom allocation

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Containers, algorithms and utilities

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ETL	Not used	Configurable	None

Components of `container` framework can invoke user-defined handlers instead of exception throwing.
Facilities from `intrusive` and `pool` can be used without exceptions

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Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	By standard*	Part of Hosted
Boost*	Not used*		**Hosted***
EASTL*	Not used*		None
ETL	Not used	Configurable	None

Explicit dependencies on standard headers in code. E.g. `<cstddef>` (freestanding) in `container` or `<functional>` (hosted) in `pool`

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EASTL*	**Not used***	C[illegible]	[illegible]ne
ETL	Not used	Configurable	None

Components with prefix “`fixed_`” in names can be used without heap allocation

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Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
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EASTL*	Not used*	Configurable	None
ETL	**Not used**		one

Library is designed to be independent from heap allocation

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Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	By standard*	Part of Hosted
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EASTL*	N		
ETL	Not used		

The frameworks are based on different design decisions and have distinct features but the core functionality is similar. Both contain alternative implementations of standard utilities and algorithms

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Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	By standard*	Part of Hosted
Boost*	Not used*	Configurable*	Hosted*
EASTL*	Not used*	**Configurable**	[illegible]
ETL	Not used	**Configurable**	[illegible]

Exception throwing, custom assertion handlers, disabled checks (reliance on external checks)

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Containers, algorithms and utilities

Framework	Heap allocation	Exceptions handling	Dependency on std
STL, Utility lib	By standard*	By standard*	Part of Hosted
Boost*	Not		Hosted*
EASTL*	Not		**None**
ETL	Not		**None**

No explicit dependencies on standard headers in the code.
Alternative implementations of standard utilities are used instead. Can be adopted for the target platform by providing required definitions

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Event type

```
class Event {
public:
     Timestamp getTimestamp() const;
//...
private:
    eastl::fixed_function<config::max_capture_list_buffer_size, void()> _function;
//...
#ifdef EVENT_DEBUG_ENABLED
    eastl::fixed_string<char, config::max_event_info_string_len, false> _event_info;
#endif
};
```

Types with fixed size storage

```
class Event {
public:
     Timestamp getTimestamp() const;
//...
private:
    eastl::fixed_function<config::max_function_capture_buffer, void()> _function;
//...
#ifdef EVENT_DEBUG_ENABLED
    eastl::fixed_string<char, config::max_event_info_string, false> _event_info;
#endif
};
```

Alternatives for standard types but without heap allocation

Containers. Custom allocator

```
std::vector<Event
     , allocator_once_returns_pointer_to_static_buffer_of_size<N>> v;

v.reserve(N);

if (v.size() < v.capacity())
    v.emplace_back(...);
```

Containers. Custom allocator

```
std::vector<Event
     , allocator_once_returns_pointer_to_static_buffer_of_size<N>> v;

v.reserve(N);

if (v.size() < v.capacity())
    v.emplace_back(...);
```

Allocator returning static buffer big enough to store N objects

Containers. Custom allocator

```
std::vector<Event
     , allocator_once_returns_pointer_to_static_buffer_of_size<N>> v;

v.reserve(N);

if (v.size() < v.capacity())
    v.emplace_back(...);
```

Single memory allocation request

Containers. Custom allocator

```
std::vector<Event
     , allocator_once_returns_pointer_to_static_buffer_of_size<N>> v;

v.reserve(N);

if (v.size() < v.capacity())
    v.emplace_back(...);
```

Redundant external checks to avoid exceptional situation. No standard customizable alternative to exception throwing. Typically abort is called if exceptions are disabled

Container compatibility

```
using queue_container = boost::container::static_vector<Event, 3>;
auto cmp_by_timestamp = [](auto const& left, auto const& right) {
    return left.getTimestamp() > right.getTimestamp();
};
using queue = std::priority_queue<Event, queue_container, decltype(cmp_by_timestamp)>;
queue q(cmp_by_timestamp);
if (q.size() < queue_container::static_capacity) {
    q.push(Event{...});
} else { /*...*/ }
auto const& top_item = q.top();
```

Container compatibility

```
using queue_container = boost::container::static_vector<Event, 3>;
auto cmp_by_timestamp = [](auto const& left, auto const
    return left.getTimestamp() > right.getTimestamp();
};
using queue = std::priority_queue<Event, queue_container,
queue q(cmp_by_timestamp);
if (q.size() < queue_container::static_capacity) {
    q.push(Event{...});
} else { /*...*/ }
auto const& top_item = q.top();
```

Fixed-capacity vector compatible with stl.

Size specified at compile time.

Alternatives are:

`eastl::fixed_vector`, `etl::vector`

Container compatibility

```
using queue_container = boost::container::static_vector<Event, 3>;
auto cmp_by_timestamp = [](auto const& left, auto const& righ
    return left.getTimestamp() > right.getTimestamp();
};
using queue = std::priority_queue<Event, queue_container, dec
queue q(cmp_by_timestamp);
if (q.size() < queue_container::static_capacity) {
    q.push(Event{...});
} else { /*...*/ }
auto const& top_item = q.top();
```

Throwing on overflow can be disabled independently from global exception settings using extra template parameter. Assertion handler (possibly custom defined) will be invoked instead

Container compatibility

```cpp
using queue_container = boost::container::static_vector<Event, 3>;
auto cmp_by_timestamp = [](auto const& left, auto const& right) {
    return left.getTimestamp() > right.getTimestamp();
};
using queue = std::priority_queue<Event, queue_container, decltype(cmp_by_timestamp)>;
queue q(cmp_by_timestamp);
if (q.size() < queue_container::static_capacity)
    q.push(Event{...});
} else { /*...*/ }
auto const& top_item = q.top();
```

Heap data structure using `static_vector` as backend storage.

Alternatives are `boost::priority_queue`, `eastl::priority_queue` and `etl::priority_queue`

Container compatibility

```
using queue_container = boost::container::static_vector<Event, 3>;
auto cmp_by_timestamp = [](auto const& left, auto const& right) {
    return left.getTimestamp() > right.getTimestamp();
};
using queue = std::priority_queue<Event, queue_container, decltype(cmp_by_timestamp)>;
queue q(cmp_by_timestamp);
if (q.size() < queue_container::static_capacity) {
    q.push(Event{...});
} else { /*...*/ }
auto const& top_item = q.top();
```

Redundant checks if exceptions are not used.

Alternatively user defined callbacks `throw_bad_alloc`, `throw_out_of_range`, … can be provided

Fixed-capacity containers

```
eastl::fixed_set<Event, 100, false
    , decltype(cmp_by_timestamp)> queue(cmp_by_timestamp);

if (queue.size() < queue.max_size()) {
    queue.insert(Event{...});
}
```

Fixed-capacity containers

```
eastl::fixed_set<Event, 100, false
    , decltype(cmp_by_timestamp)> queue(cmp_by_timestamp);

if (queue.size() < queue.max_size()) {
    queue.insert(Event{...});
}
```

Available in EASTL along with `fixed_map`, `fixed_hash_map`, etc. Alternative is `etl::set`

Fixed-capacity containers

```
eastl::fixed_set<Event, 100, false
    , decltype(cmp_by_timestamp)> queue(cmp_by_timestamp);

if (queue.size() < queue.max_size()) {
    queue.insert(Event{...});
}
```

Maximum capacity

Fixed-capacity containers

```
eastl::fixed_set<Event, 100, false
    , decltype(cmp_by_timestamp)> queue(cmp_by_timestamp);

if (queue.size() < queue.max_size()) {
    queue.insert(Event{...});
}
```

Heap allocation as fallback is disabled

Fixed-capacity containers

```
eastl::fixed_set<Event, 100, false
    , decltype(cmp_by_timestamp)> queue(cmp_by_timestamp);

if (queue.size() < queue.max_size()) {
    queue.insert(Event{...});
}
```

For EASTL and ETL three options are available: exceptions, custom assert handlers or disabled internal checks

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};
boost::intrusive::set<Event
     , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(cmp_by_timestamp);

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer[3];
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};

boost::intrusive::set<Event
     , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(cmp_by_time

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer[3];
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Service data block for intrusive data structure

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};
boost::intrusive::set<Event
    , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer[3];
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Intrusive set. No allocation is performed on insertion

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};
boost::intrusive::set<Event
     , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(cmp_by_timestamp);

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer[N];
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Aligned storage for N `Event` objects

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};
boost::intrusive::set<Event
    , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(cmp_by_timestamp);

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer[N];
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Free-list pool with block size equal to `sizeof(Event)`

Pool allocation and intrusive containers

```
class Event : public boost::intrusive::set_base_hook<> {/*...*/};
boost::intrusive::set<Event
    , boost::intrusive::compare<decltype(cmp_by_timestamp)>> q(cmp_by_timestamp);

std::aligned_storage_t<sizeof(Event), alignof(Event)> buffer
boost::simple_segregated_storage<size_t> storage;
storage.add_block(buffer, sizeof(buffer), sizeof(Event));

auto mem = storage.malloc();
if (mem) q.insert(*new (mem) Event{...});
```

Memory block allocation and object construction. Insertion into `set` will not throw if predicate is not throwing

Custom allocation

```
struct Event {
    static void* operator new(std::size_t sz);
    static void operator delete(void* p);
};

void* Event::operator new(std::size_t)
{
    return event_allocator::allocate();
}

void Event::operator delete(void* p)
{
    return event_allocator::free(p);
}
```

Custom allocation

```
struct Event {
    static void* operator new(std::size_t sz);
    static void operator delete(void* p);
};

void* Event::operator new(std::size_t)
{
    return event_allocator::allocate();
}

void Event::operator delete(void* p)
{
    return event_allocator::free(p);
}
```

Static methods access shared allocator

Custom allocation

```
template <uint32_t Id>
struct Event {
    static void* operator new(std::size_t sz);
    static void operator delete(void* p);
};

template <uint32_t Id>
void* Event<id>::operator new(std::size_t)
{
    return event_allocator<Id>::allocate();
}

template <uint32_t Id>
void Event<Id>::operator delete(void* p)
{
    return event_allocator<Id>::free(p);
}
```

Different instantiations will access different allocator instances

Custom allocation

```
template <uint32_t Id>
struct Event {
    static void* operator new(std::size_t sz);
    static void operator delete(void* p);
};

template <uint32_t Id>
void* Event<id>::operator new(std::size_t)
{
    return event_allocator<Id>::allocate();
}

template <uint32_t Id>
void Event<Id>::operator delete(void* p)
{
    return event_allocator<Id>::free(p);
}
```

```
template <uint32_t Id>
class event_allocator {
    static void* allocate();
    static buffer static_buffer;
};

template <uint32_t Id>
buffer event_allocator<Id>
    ::static_buffer;
```

Polymorphism based on variant

```
struct Spi { void send(); };

struct Uart { void send(); };

using transports = std::variant<Spi, Uart>;

transports make_transport() { return Uart{}; }


auto transport = make_transport();

std::visit([](auto &tr) { tr.send(); }, transport);
```

Polymorphism based on variant

```
struct Spi { void send(); };

struct Uart { void send(); };

using transports = std::variant<Spi, Uart>;

transports make_transport() { return Uart{}; }


auto transport = make_transport();

std::visit([](auto &tr) { tr.send(); }, transport);
```

Factory method returns `variant`

No heap allocation guaranteed.

Alternatives: `boost::variant`, `eastl::variant`, `etl::variant`

Polymorphism based on variant

```
struct Spi { void send(); };

struct Uart { void send(); };

using transports = std::variant<Spi, Uart>;

transports make_transport() { return Uart{}; }


auto transport = make_transport();

std::visit([](auto &tr) { tr.send(); }, transport);
```

Duck-typing inside generic lambda

Error handling without exceptions

```
std::optional<Data> read_data();
//...
if (const auto &data = read_data(); data) {
    process_data(*data);
} else {
    //...
}
```

Error handling without exceptions

```
std::optional<Data> read_data();
//...
if (const auto &data = read_data(); data) {
    process_data(*data);
} else {
    //...
}
```

Guaranteed not to allocate.

Alternatives: `boost::optional`, `eastl::optional`, `etl::optional`

Error handling without exceptions

```
std::optional<Data> read_data();
//...
if (const auto &data = read_data(); data) {
    process_data(*data);
} else {
    //...
}
// or
template<typename T>
using value_or_error = std::variant<T, std::error_code>;
value_or_error<Data> read_data();
```

Some imitation of proposed `expected` type.

Guaranteed not to allocate.

`boost::outcome` is an advanced alternative

Containers, algorithms and utilities. Summary

- Although with some limitations standard library can be used in the embedded environment
- Multiple 3rd-party frameworks offer large choice of standard-like and non-standard containers and utilities addressing heap allocation and exception handling limitations
- In case of unavailability of standard library several 3rd-party frameworks can be used as a substitution

Conclusion

- Best practices – well-known to the C++ community – are essential in embedded development
- C++ language has mechanisms enabling testability and portability of the embedded code (encapsulation, polymorphism)
- Availability of the 3rd party frameworks applicable for embedded development facilitates development
- There is an overlap between embedded and non-embedded domains (HPT, game-dev). Knowledge exchange is beneficial

Thank you!

Questions?