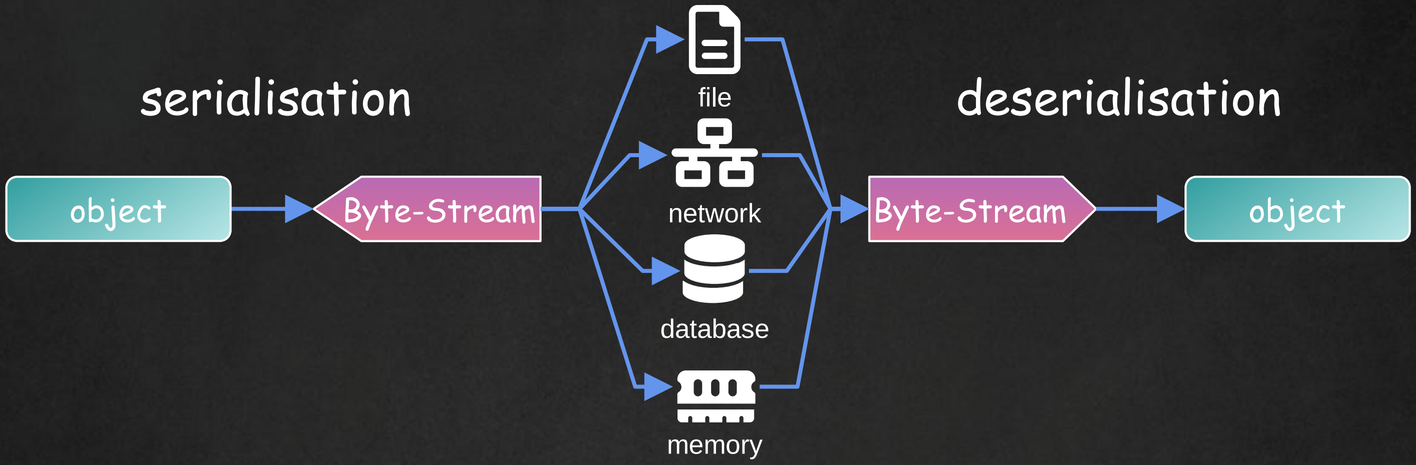
Yet-Another-Serialiser (YAS)

or: why we are not reusing and opted to write yet another custom data serialiser

Ralph J. Steinhagen



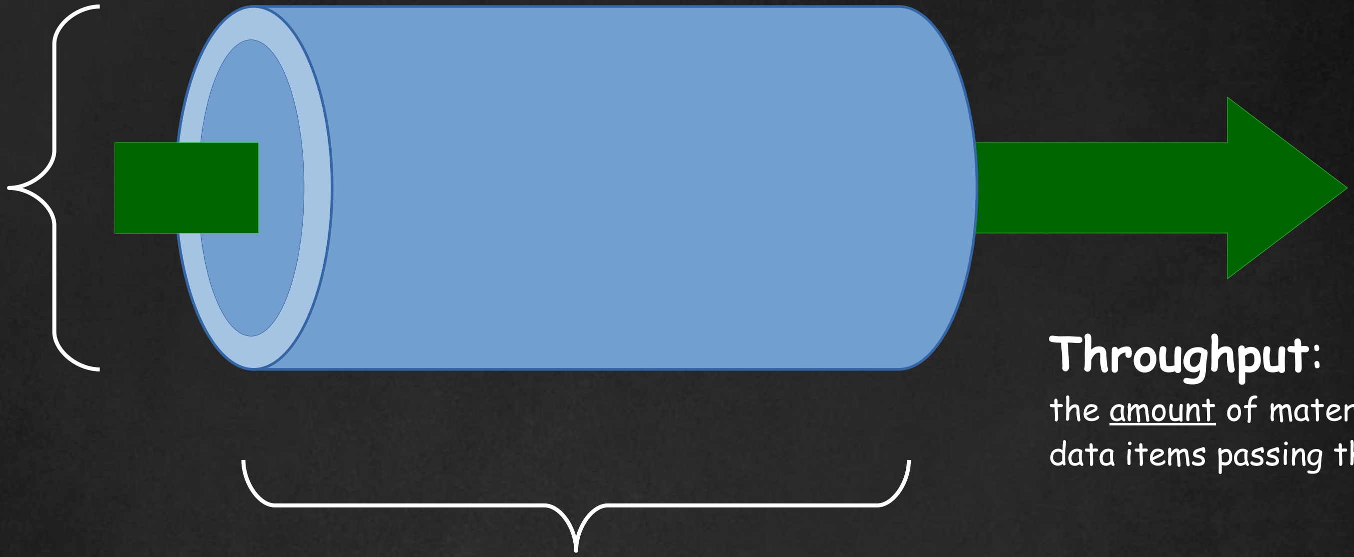
- Serialisation is key when information has to be transmitted, stored and later retrieved by (often quite) different subsystems, architectures and/or programming languages.
  - with a multitude of different serialiser libraries, a non-negligible subset of these claim to be the fastest, most efficient, easiest-to-use or *<add your favourite superlative here>*
  - this is true for most libraries' original use-case but often breaks down for other applications.
- This talk aims at motivating our compile-time reflection based approach used in OpenCMW

Our FAIR/OpenCMW focus

1. **performance: minimise end-to-end latency** between server-/client- processing worker function
2. facilitate **multi-protocol** implementations & **protocol evolution**
   (i.e. loose coupling between server-/client-side data object definitions)
3. decoupling client-/server-side logic/worker from wire-formats
   (i.e. independent on specific format: binary@1, binary#2, JSON, XML, YML, …)
4. **derive schemas directly class structures & basic types** (PoCos/PoJos)
   rather than a 3rd-party Interface-Description-Languages (IDL) definitions
5. allow **user-level schema extensions** through optional custom (de-)serialiser routines
6. **self-documented data-structures** to communicate the data-exchange-API-intend to the client
7. **minimise code-bloat** ↔ performance (L1/L2/L3 cache sizes) & minimises maintenance overhead
8. **test driven development**
9. **free- and open-source code w/o strings-attached**

Performance

minimise end-to-end latency



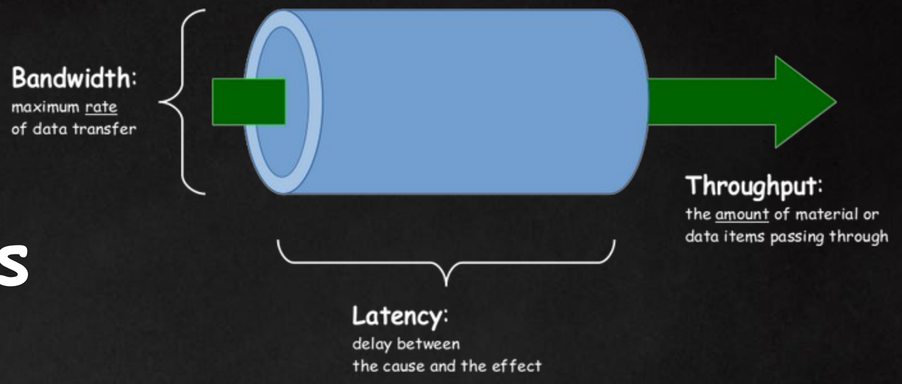
Bandwidth:
maximum rate
of data transfer

Throughput:
the amount of material or
data items passing through

Latency:
delay between
the cause and the effect

- Some trade-offs that affect bandwidth and latency
  - bandwidth: meta-data, compression,
  - latency: numerical complexity (e.g. due to compression), necessity to read-ahead

1. Performance



Bandwidth:
maximum rate
of data transfer

Throughput:
the amount of material or
data items passing through

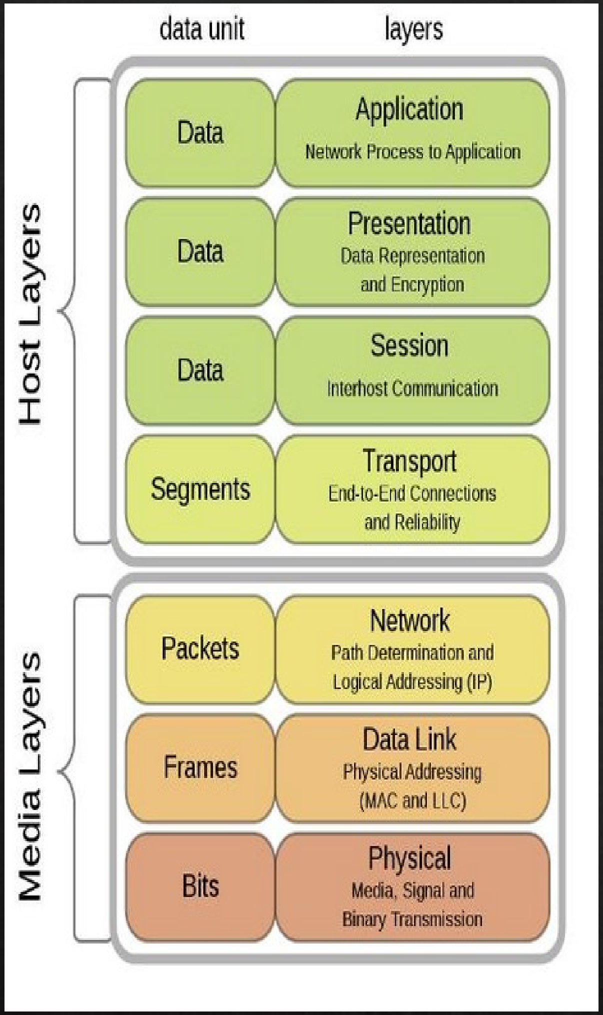
Latency:
delay between
the cause and the effect

Some Trade-offs/Choices

- meta-data (e.g. field name, hashes, type, size, …)
  - ⊗ overhead, esp. if server & client share same object definition and CPU architecture
    (N.B. some "fast" serialiser transmit plain POCOs)
  - ✓ supports different architecture (e.g. ARM, x86, PowerPC) and programming languages/tools (e.g. C++, Java, Python)
  - ✓ protocol evolution i.e. decouples server/client object definition
    e.g. server can add/remove/change new field while client reads only fields that are relevant to its application
- compression/size i.e. reduces amount of data
  notably: only transmit what is actually needed by the client
  - ✓ less data → less to encode → less to transmit → lower latency
    esp. for network- or bus-limited applications ↔ internet, CAN, low-power wifi/IoT, …
  - ⊗ numerical compression complexity increases CPU load/latency
    esp. dominant if the main/cache memory bandwidth limit (i.e. > few GB/s)
- read-ahead meta-information i.e. storing absolute markers for next field
  - ⊗ wastes additional bytes for type and/or size information
  - ✓ some data structure where the (skipping) length of the wire-format is only known after de-/encoding
    - e.g. 'float' → String conversion: '0.0' … '0.12345678' … '3.402823466E+38'
    - e.g. 'std::map<std::string, my_data>' → binary/string wire-format
- intermediate representation .e.g. wire-format → std::map<std::string, meta_data> → object
  - ✓ run-time parsing and/or unknown object formats
  - ⊗ compile-time compiler/performance optimisations & may need to read the wire-format multiple times

2. Multi-Protocol Support

& protocol evolution

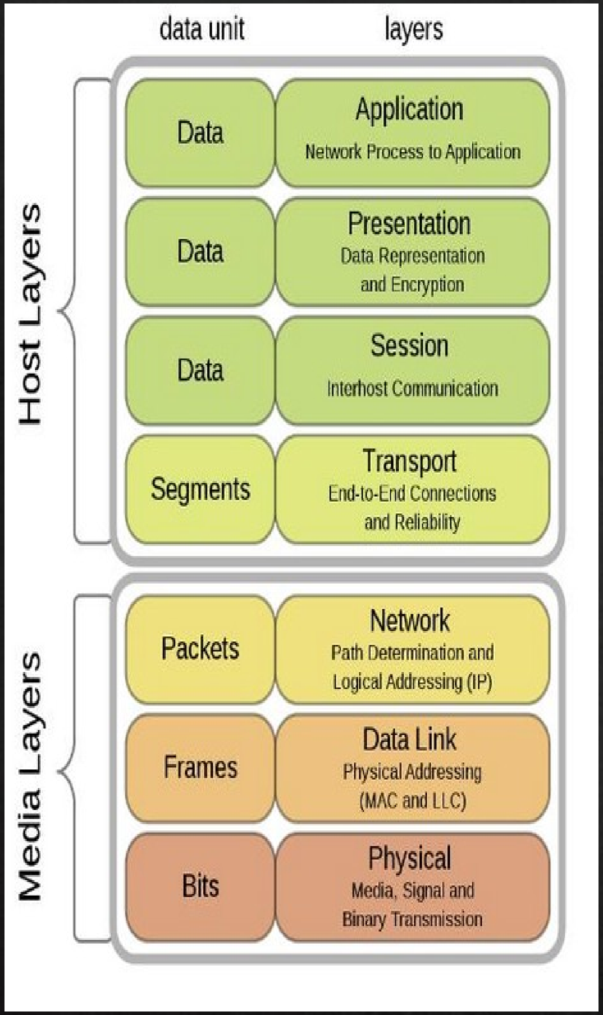

data unit
layers
Host Layers
Data
Application
Network Process to Application
Data
Presentation
Data Representation and Encryption
Data
Session
Interhost Communication
Segments
Transport
End-to-End Connections and Reliability
Media Layers
Packets
Network
Path Determination and Logical Addressing (IP)
Frames
Data Link
Physical Addressing (MAC and LLC)
Bits
Physical
Media, Signal and Binary Transmission

protocol stack of the OSI model

- There are a multitude of middleware protocols
  - e.g. Kafka, ActiveMQ, Flow, myriad of <ZeroMQ-based>, MQTT, RabbitMQ, Mosquitto, HTTP, OpenCMW, ...

2. Multi-Protocol Support

& protocol evolution

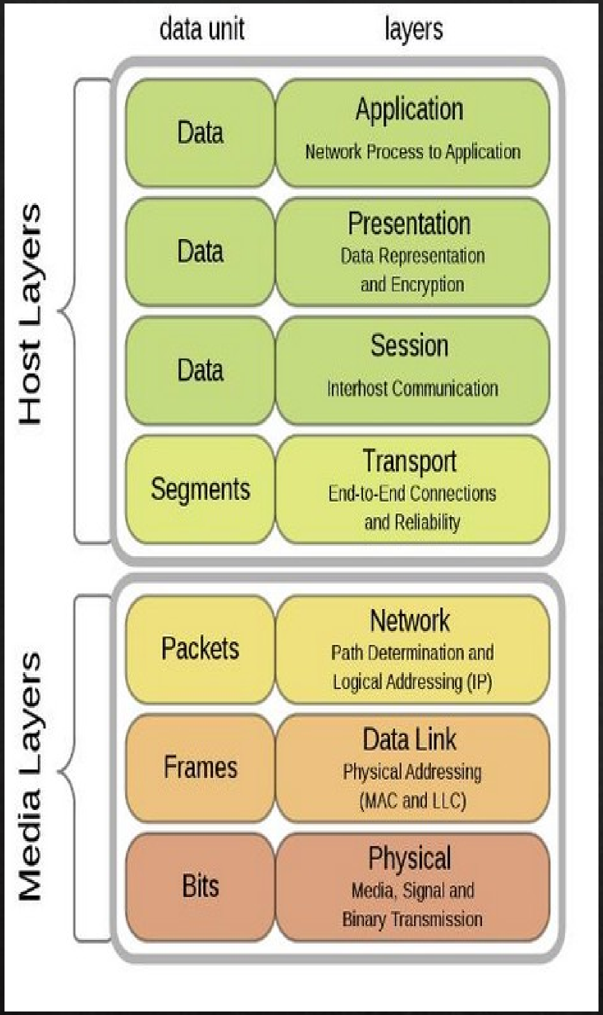

data unit
layers
Host Layers
Data
Application
Network Process to Application
Data
Presentation
Data Representation and Encryption
Data
Session
Interhost Communication
Segments
Transport
End-to-End Connections and Reliability
Media Layers
Packets
Network
Path Determination and Logical Addressing (IP)
Frames
Data Link
Physical Addressing (MAC and LLC)
Bits
Physical
Media, Signal and Binary Transmission

protocol stack of the OSI model

- There are a multitude of middleware protocols
  - e.g. Kafka, ActiveMQ, Flow, myriad of <ZeroMQ-based>, MQTT, RabbitMQ, Mosquitto, HTTP, OpenCMW, ...
- and serialiser implementation out there
  - e.g. Cap’n Proto, FlatBuffer, Protobuff, XML, YML, JSON, ‘CSV’, HTML, SBE, YaS, ...

2. Multi-Protocol Support

& protocol evolution

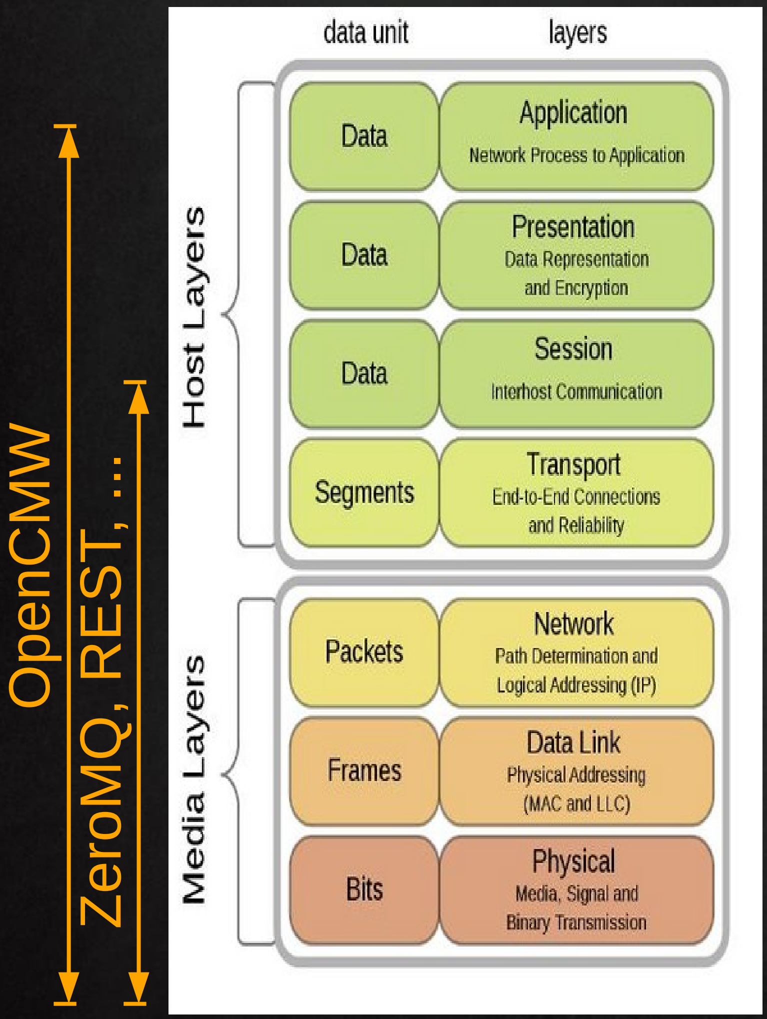

data unit
layers
Host Layers
Media Layers
Data
Application
Network Process to Application
Data
Presentation
Data Representation and Encryption
Data
Session
Interhost Communication
Segments
Transport
End-to-End Connections and Reliability
Packets
Network
Path Determination and Logical Addressing (IP)
Frames
Data Link
Physical Addressing (MAC and LLC)
Bits
Physical
Media, Signal and Binary Transmission

protocol stack of the OSI model

- There are a multitude of middleware protocols
  - e.g. Kafka, ActiveMQ, Flow, myriad of <ZeroMQ-based>, MQTT, RabbitMQ, Mosquitto, HTTP, OpenCMW, ...
- and serialiser implementation out there
  - e.g. Cap’n Proto, FlatBuffer, Protobuff, XML, YML, JSON, ‘CSV’, HTML, SBE, YaS, ...
- highly biased topic:
  some aim at world-domination but reality in larger facilities consists often of a diverse middleware landscape
  → nearly always need some adapter, proxies, …
  - high-risk of “onion-layered” integrations
    N.B. OpenCMW aims at solving this issue through ‘composition’

2. OpenCMW 's Majordomo Transport Protocol

aims at an extendable full protocol stack implementation



data unit
layers
Host Layers
Data
Application
Network Process to Application
Data
Presentation
Data Representation and Encryption
Data
Session
Interhost Communication
Segments
Transport
End-to-End Connections and Reliability
Media Layers
Packets
Network
Path Determination and Logical Addressing (IP)
Frames
Data Link
Physical Addressing (MAC and LLC)
Bits
Physical
Media, Signal and Binary Transmission
OpenCMW
ZeroMQ, REST, ...

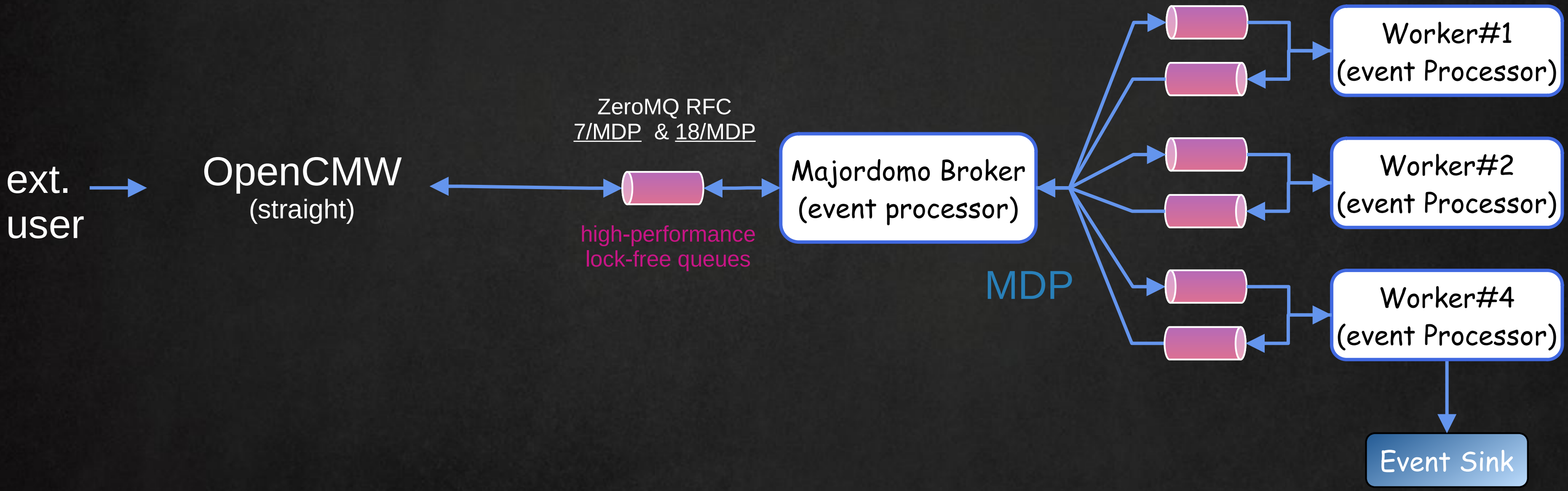
protocol stack of the OSI model

… with (optional) 'batteries' included:

- Transport protocols:
  - Majordomo (ZeroMQ: RFC 7/MDP & 18/MDP),
  - RDA3 (proprietary GSI/CERN transport
  - HTTP/REST (long-polling, SSE): web-services, routable to non-GSI/FAIR networks
  - RADIO/DISH (low-latency UDP) – WIP
  - *… <add your protocol here>*
- Serialisers
  - YaS (binary): annotated type- and physical unit-safe
  - CmwLight (binary): ACC-specific binary protocol
  - JSON (text): data exchange with web-based REST clients
  - YML (text): service config management (human readable)
  - HTML: server-side rendered fixed-displays (+WASM), expert diagnostics tools, ...
  - *… <add your serialiser here>*
- RPC/Streaming call-backs: lambda → convenience classes
- lock-free circular buffers → event sourcing pattern
- thread-affinity, -tools & -pools
- settings management, ...

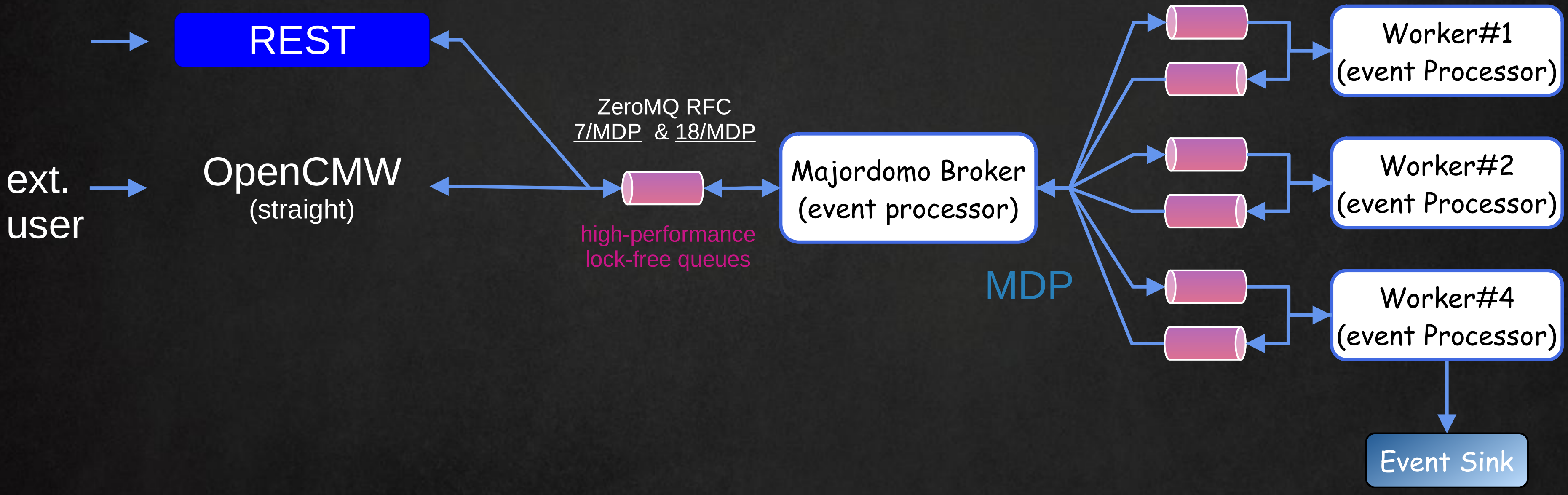
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



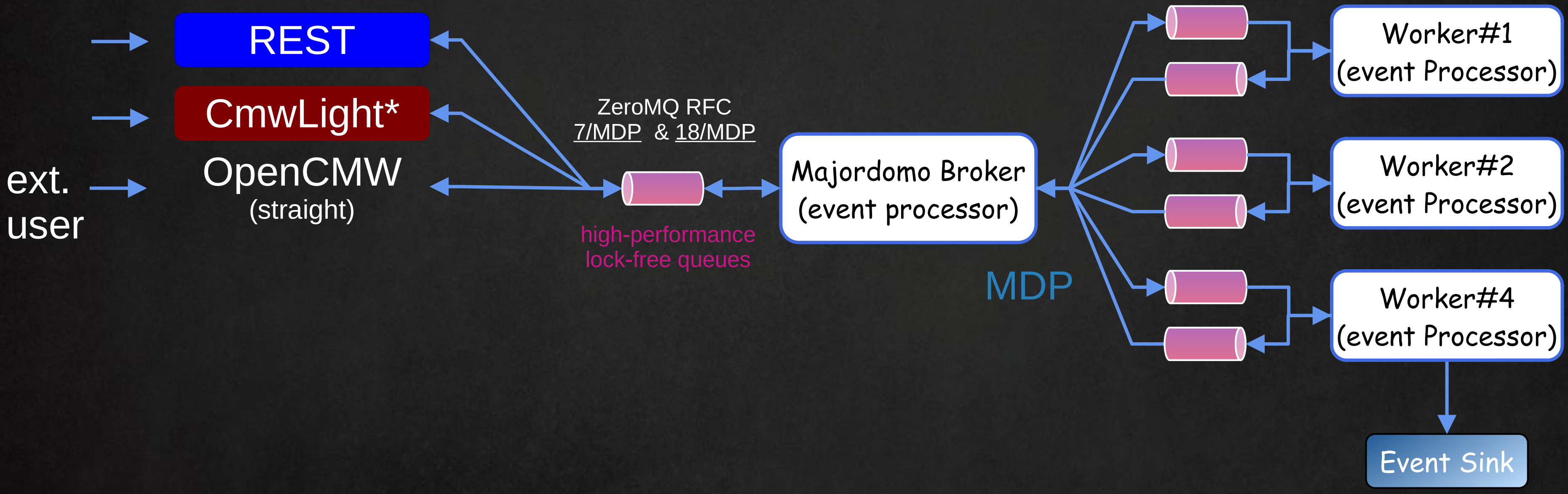
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



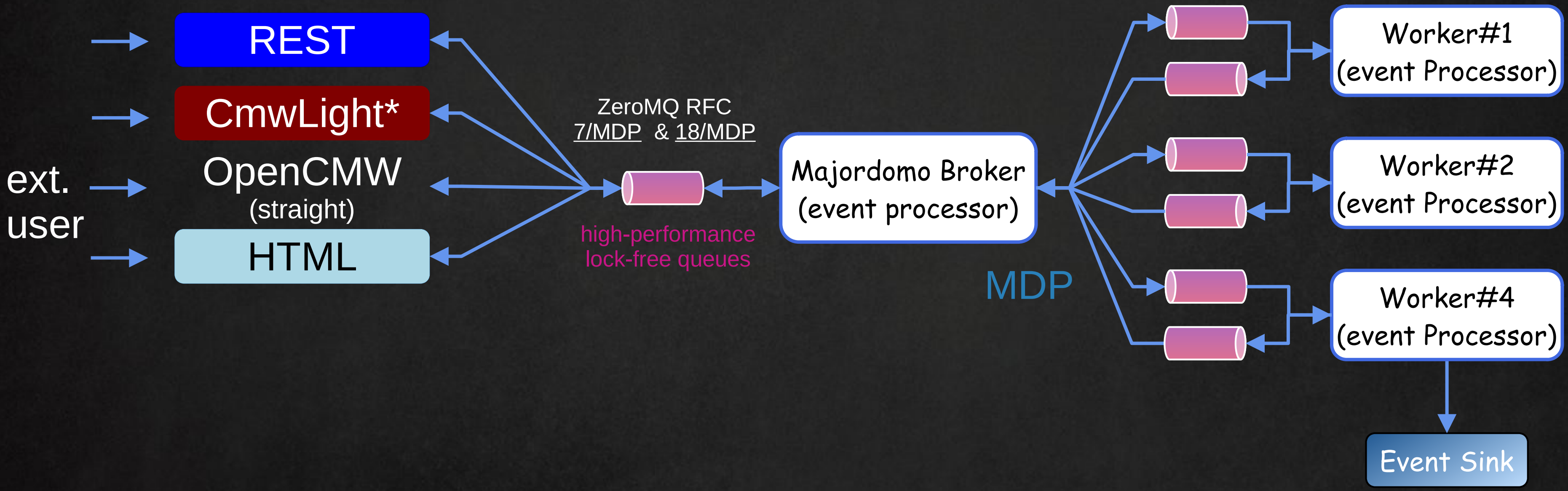
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



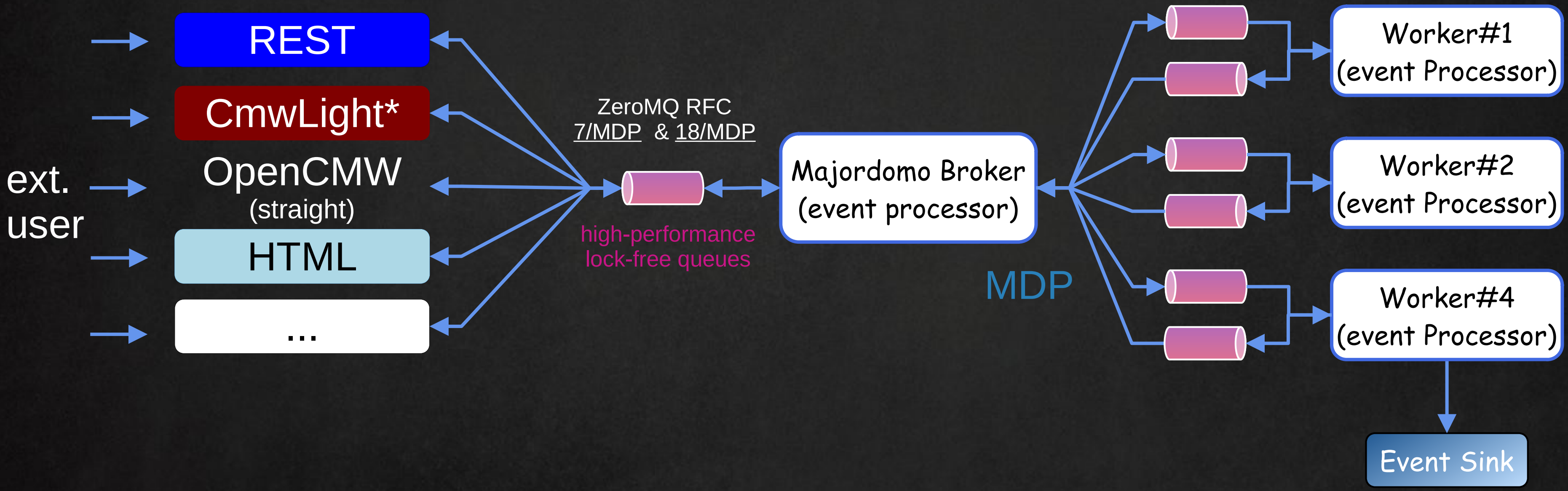
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



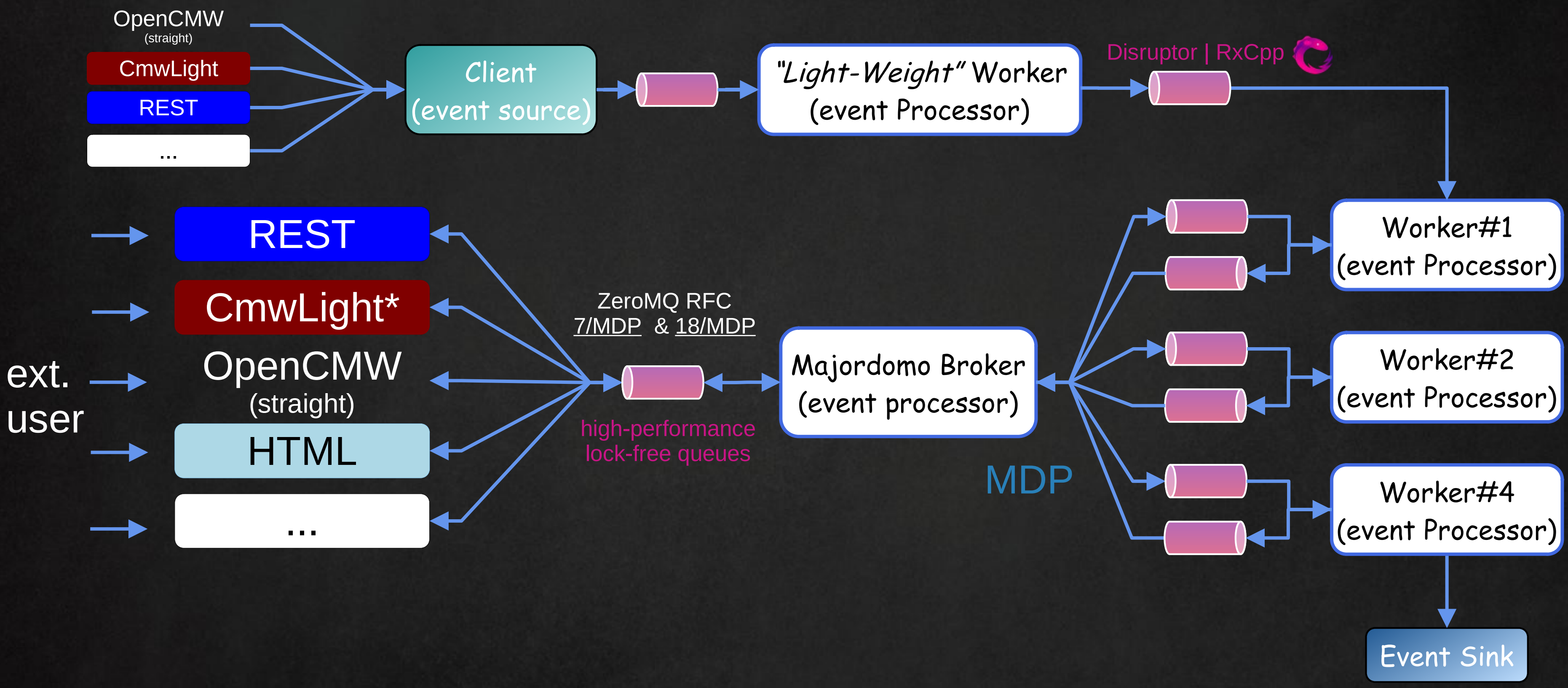
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



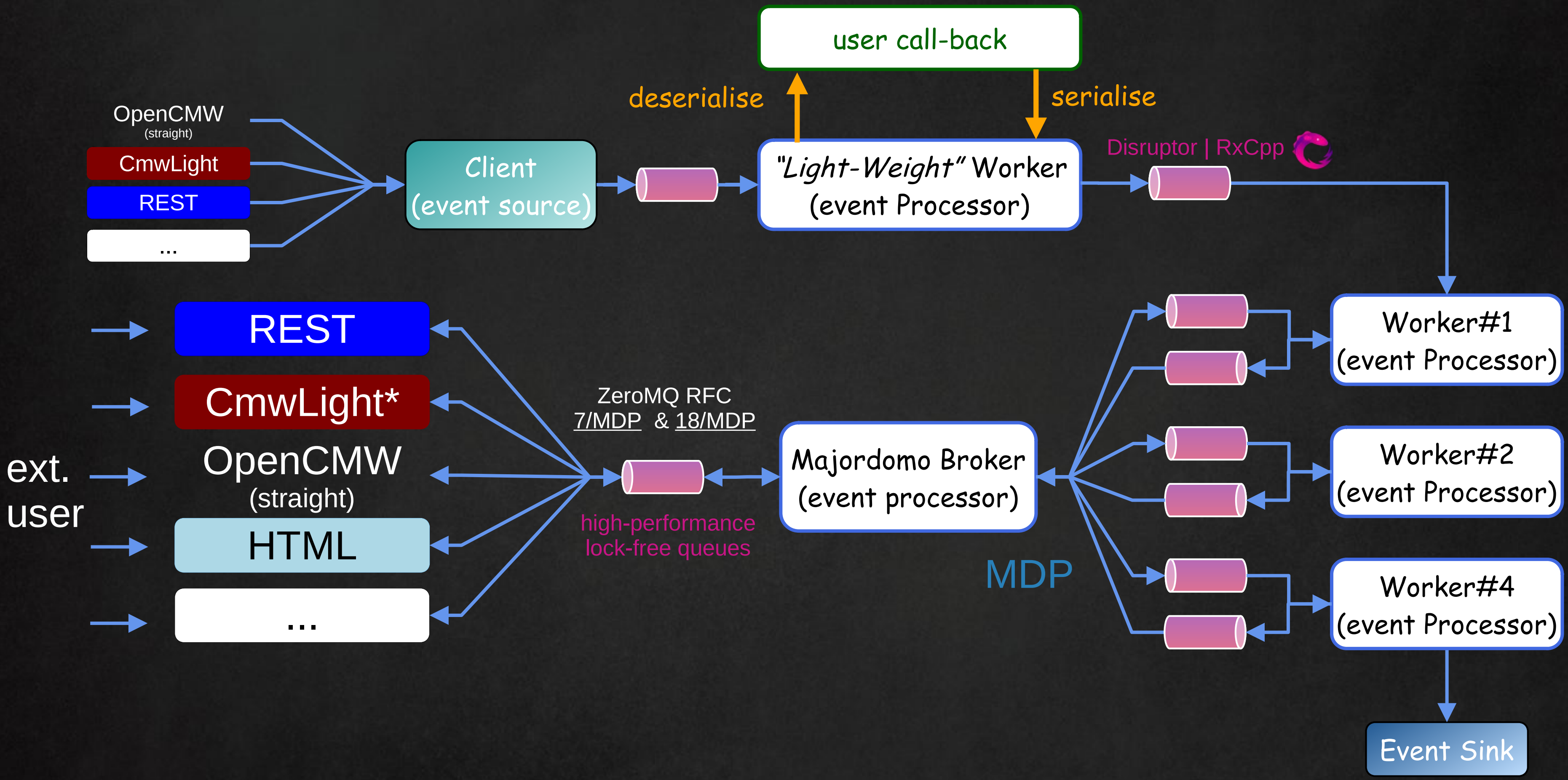
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



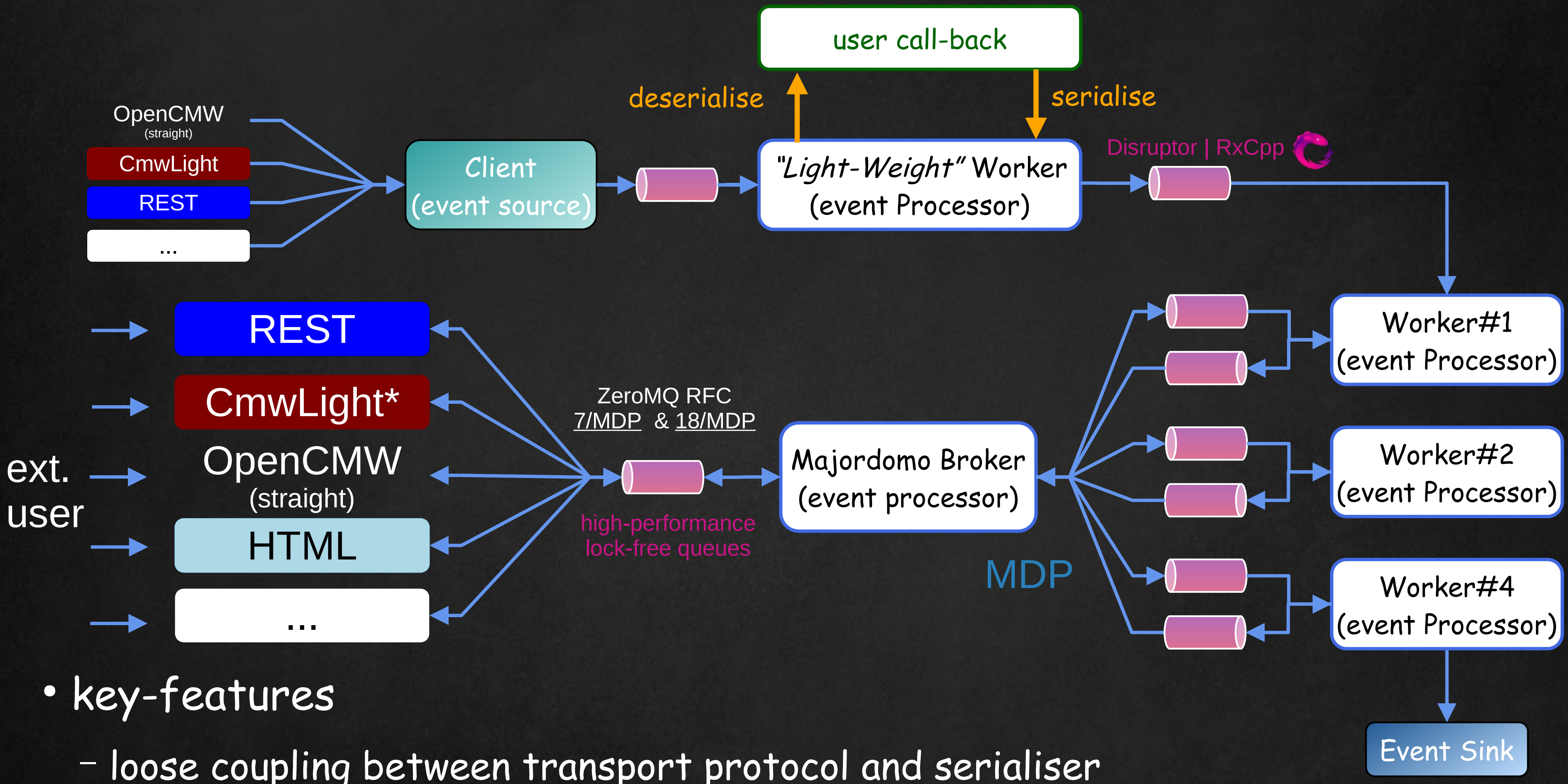
3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



3. decoupling logic ↔ wire-format

OpenCMW's Microservice Architecture



- key-features
  - loose coupling between transport protocol and serialiser
  - worker logic independent from specific wire-format

3. decoupling logic ↔ wire-format

basic REQ/REP & PUB/SUB example

```
struct AddressRequest {                              // request domain-object
    int id;
};
ENABLE_REFLECTION_FOR(AddressRequest, id)
```

```
struct AddressEntry {                               // reply domain-object
    int                                                  id;
    Annotated<std::string, NoUnit, "Name of the person"> name;
    std::string                                          street;
    Annotated<int, NoUnit, "Number">                     streetNumber;
    std::string                                          postalCode;
    std::string                                          city;
    bool                                                 isCurrent;
};
ENABLE_REFLECTION_FOR(AddressEntry, name, street, streetNumber, postalCode, city, isCurrent)
```

3. decoupling logic ↔ wire-format

basic REQ/REP & PUB/SUB example

```
struct AddressRequest {                               // request domain-object
    int id;
};
ENABLE_REFLECTION_FOR(AddressRequest, id)
```

```
struct AddressEntry {                                // reply domain-object
    int                                                     id;
    Annotated<std::string, NoUnit, "Name of the person"> name;
    std::string                                             street;
    Annotated<int, NoUnit, "Number">                        streetNumber;
    std::string                                             postalCode;
    std::string                                             city;
    bool                                                    isCurrent;
};
ENABLE_REFLECTION_FOR(AddressEntry, name, street, streetNumber, postalCode, city, isCurrent)
```

```
struct TestContext {
    TimingCtx      ctx;
    MIME::MimeType contentType = MIME::HTML;
};
ENABLE_REFLECTION_FOR(TestContext,ctx,contentType)

                    filter/query domain-object
```

3. decoupling logic ↔ wire-format

basic REQ/REP & PUB/SUB example

```
struct AddressRequest {                                    // request domain-object
    int id;
};
ENABLE_REFLECTION_FOR(AddressRequest, id)
```

```
struct AddressEntry {                                     // reply domain-object
    int                                                   id;
    Annotated<std::string, NoUnit, "Name of the person"> name;
    std::string                                           street;
    Annotated<int, NoUnit, "Number">                      streetNumber;
    std::string                                           postalCode;
    std::string                                           city;
    bool                                                  isCurrent;
};
ENABLE_REFLECTION_FOR(AddressEntry, name, street, streetNumber, postalCode, city, isCurrent)
```

```
struct TestContext {
    TimingCtx      ctx;
    MIME::MimeType contentType = MIME::HTML;
};
ENABLE_REFLECTION_FOR(TestContext,ctx,contentType)

                        filter/query domain-object
```

```
struct TestAddressHandler {
    std::unordered_map<int, AddressEntry> _entries;

    TestAddressHandler() { _entries.emplace(42, AddressEntry{ 42, "Santa Claus", "Elf Road", 123, "88888", "North Pole", true }); }

    void operator()(opencmw::majordomo::RequestContext &rawCtx, const TestContext & /*requestContext*/, const AddressRequest &request,
                                                                  TestContext & /*replyContext*/,         AddressEntry   &reply) {
        if (rawCtx.request.command() == Command::Get) {
            const auto it = _entries.find(request.id);
            if (it == _entries.end()) {
                reply = _entries.cbegin()->second;
            } else {
                reply = it->second;
            }
        } else if (rawCtx.request.command() == Command::Set) {
            /* do nothing */
        }
    }
};
```

3. decoupling logic ↔ wire-format

basic REQ/REP & PUB/SUB example

```
struct AddressRequest {                              // request domain-object
    int id;
};
ENABLE_REFLECTION_FOR(AddressRequest, id)
```

```
struct AddressEntry {                                    // reply domain-object
    int                                                     id;
    Annotated<std::string, NoUnit, "Name of the person"> name;
    std::string                                             street;
    Annotated<int, NoUnit, "Number">                        streetNumber;
    std::string                                             postalCode;
    std::string                                             city;
    bool                                                    isCurrent;
};
ENABLE_REFLECTION_FOR(AddressEntry, name, street, streetNumber, postalCode, city, isCurrent)
```

```
struct RequestContext {
    const MdpMessage request;
    MdpMessage       reply;
    MIME::MimeType   mimeType = MIME::BINARY;

};
                    low-level expert-dev fall-back
```

```
struct TestContext {
    TimingCtx      ctx;
    MIME::MimeType contentType = MIME::HTML;
};
ENABLE_REFLECTION_FOR(TestContext,ctx,contentType)

                    filter/query domain-object
```

```
struct TestAddressHandler {
    std::unordered_map<int, AddressEntry> _entries;

    TestAddressHandler() { _entries.emplace(42, AddressEntry{ 42, "Santa Claus", "Elf Road", 123, "88888", "North Pole", true }); }

    void operator()(opencmw::majordomo::RequestContext &rawCtx, const TestContext & /*requestContext*/, const AddressRequest &request,
                                                                TestContext & /*replyContext*/,         AddressEntry   &reply) {
        if (rawCtx.request.command() == Command::Get) {
            const auto it = _entries.find(request.id);
            if (it == _entries.end()) {
                reply = _entries.cbegin()->second;
            } else {
                reply = it->second;
            }
        } else if (rawCtx.request.command() == Command::Set) {
            /* do nothing */
        }
    }
};
```

3. decoupling logic ↔ wire-format

basic REQ/REP & PUB/SUB example

```
struct AddressRequest {                                // request domain-object
    int id;
};
ENABLE_REFLECTION_FOR(AddressRequest, id)
```

```
struct AddressEntry {                                  // reply domain-object
    int                                                      id;
    Annotated<std::string, NoUnit, "Name of the person"> name;
    std::string                                              street;
    Annotated<int, NoUnit, "Number">                         streetNumber;
    std::string                                              postalCode;
    std::string                                              city;
    bool                                                     isCurrent;
};
ENABLE_REFLECTION_FOR(AddressEntry, name, street, streetNumber, postalCode, city, isCurrent)
```

```
struct RequestContext {
    const MdpMessage request;
    MdpMessage       reply;
    MIME::MimeType   mimeType = MIME::BINARY;
};
                 low-level expert-dev fall-back
```

key: transport and wire-format are independent

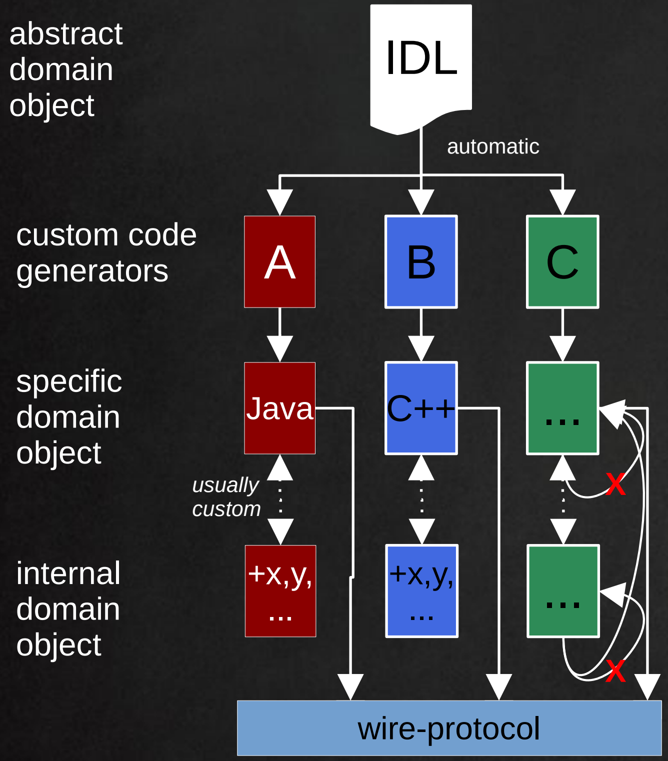
```
struct TestContext {
    TimingCtx      ctx;
    MIME::MimeType contentType = MIME::HTML;
};
ENABLE_REFLECTION_FOR(TestContext,ctx,contentType)

                         filter/query domain-object
```

```
struct TestAddressHandler {
    std::unordered_map<int, AddressEntry> _entries;

    TestAddressHandler() { _entries.emplace(42, AddressEntry{ 42, "Santa Claus", "Elf Road", 123, "88888", "North Pole", true }); }

    void operator()(opencmw::majordomo::RequestContext &rawCtx, const TestContext & /*requestContext*/, const AddressRequest &request,
                                                                     TestContext & /*replyContext*/,         AddressEntry   &reply) {
        if (rawCtx.request.command() == Command::Get) {
            const auto it = _entries.find(request.id);
            if (it == _entries.end()) {
                reply = _entries.cbegin()->second;
            } else {
                reply = it->second;
            }
        } else if (rawCtx.request.command() == Command::Set) {
           /* do nothing */
        }
    }
};
```

4. Core Serialiser Choice

derive schemas directly class structures & basic types

- classic IDL-based design:
  (i.e. protobuf, FastBuffer, CapNProto, …)

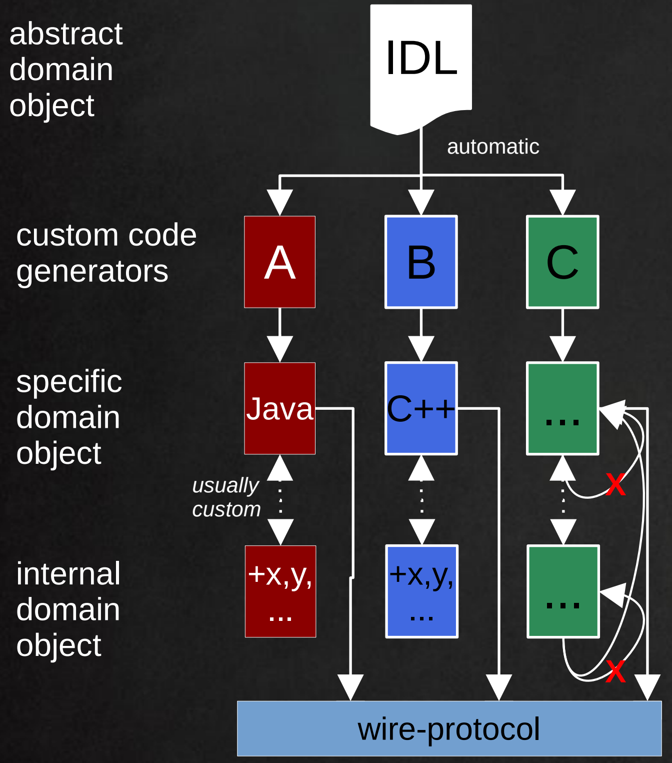


- either: generic serialiser not necessarily optimised for our data use-case
- or: need to maintain multiple custom generators
  → custom (eventually buggy/out-dated) generator
- users need to learn IDL syntax & build-system magic
- requires very disciplined developers (three interfaces to maintain)

4. Core Serialiser Choice

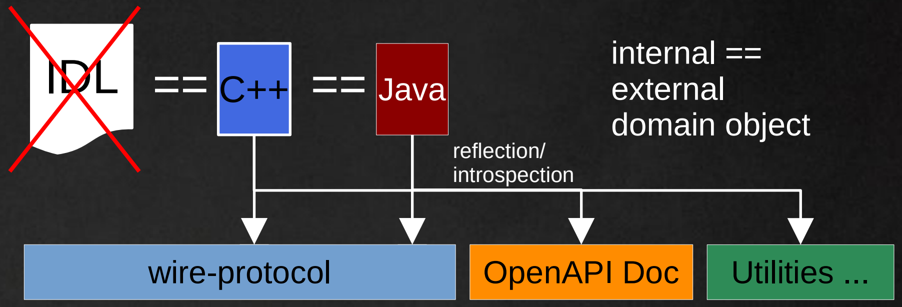
derive schemas directly class structures & basic types

- classic IDL-based design:
  (i.e. protobuf, FastBuffer, CapNProto, …)



- either: generic serialiser not necessarily optimised for our data use-case
- or: need to maintain multiple custom generators
  → custom (eventually buggy/out-dated) generator
- users need to learn IDL syntax & build-system magic
- requires very disciplined developers (three interfaces to maintain)

- static compile-time based reflection
  (IDL is identical to PoCo/PoJo)



- **cognitive complexity reduction**
  regardless of primary programming language preference:
  everyone can read & comprehend basic C++/Java/... class definitions
- **relies on existing Java & C++23 standard** (refl-cpp: visitor-pattern)
  → **less external dependencies**
  → **very little custom code to maintain since most is std::c++**
- allows less disciplined/new developers (one interface to maintain)
- self-describing format, OpenAPI definitions, utilities, ….
- turned out to be more performant that most generic serialisers ...

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```cpp
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
    for_each(refl::reflect(value).members, [&](const auto member, const auto fieldIndex) {
        auto &&fieldValue = member(value);
        using UnwrappedMemberType = std::remove_reference_t<decltype(getAnnotatedMember(unwrapPointer(fieldValue)))>;
        FieldDescription auto field = …;
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
    for_each(refl::reflect(value).members, [&](const auto member, const auto fieldIndex) {
        auto &&fieldValue = member(value);
        using UnwrappedMemberType = std::remove_reference_t<decltype(getAnnotatedMember(unwrapPointer(fieldValue)))>;
        FieldDescription auto field = …;

        if constexpr (isReflectableClass<UnwrappedMemberType>()) { // […] field is a nested data-structure
            // […] write leading start-marker
            serialise<protocol, writeMetaInfo>(buffer, getAnnotatedMember(unwrapPointer(fieldValue)), field); // recursive call
            // […] write trailing stop-marker
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
    for_each(refl::reflect(value).members, [&](const auto member, const auto fieldIndex) {
        auto &&fieldValue = member(value);
        using UnwrappedMemberType = std::remove_reference_t<decltype(getAnnotatedMember(unwrapPointer(fieldValue)))>;
        FieldDescription auto field = …;

        if constexpr (isReflectableClass<UnwrappedMemberType>()) { // […] field is a nested data-structure
            // […] write leading start-marker
            serialise<protocol, writeMetaInfo>(buffer, getAnnotatedMember(unwrapPointer(fieldValue)), field); // recursive call
            // […] write trailing stop-marker
        } else { // […] field is a (possibly annotated) primitive type → write (optional) field meta-data and primitive value
            IoSerialiser<protocol, writeMetaInfo>(buffer, field, getAnnotatedMember(unwrapPointer(fieldValue)));
        }
    });
}
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
    for_each(refl::reflect(value).members, [&](const auto member, const auto fieldIndex) {
        auto &&fieldValue = member(value);
        using UnwrappedMemberType = std::remove_reference_t<decltype(getAnnotatedMember(unwrapPointer(fieldValue)))>;
        FieldDescription auto field = …;

        if constexpr (isReflectableClass<UnwrappedMemberType>()) { // […] field is a nested data-structure
            // […] write leading start-marker
            serialise<protocol, writeMetaInfo>(buffer, getAnnotatedMember(unwrapPointer(fieldValue)), field); // recursive call
            // […] write trailing stop-marker
        } else { // […] field is a (possibly annotated) primitive type → write (optional) field meta-data and primitive value
            IoSerialiser<protocol, writeMetaInfo>(buffer, field, getAnnotatedMember(unwrapPointer(fieldValue)));
        }
    });
}
```

… similar for deserialise function

(albeit ~150 lines of code)

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<SerialiserProtocol protocol, bool writeMetaInfo = true>
constexpr void serialise(IoBuffer &buffer, ReflectableClass auto const &value, FieldDescription auto const parent) { // […] N.B. simplified
    for_each(refl::reflect(value).members, [&](const auto member, const auto fieldIndex) {
        auto &&fieldValue = member(value);
        using UnwrappedMemberType = std::remove_reference_t<decltype(getAnnotatedMember(unwrapPointer(fieldValue)))>;
        FieldDescription auto field = …;

        if constexpr (isReflectableClass<UnwrappedMemberType>()) { // […] field is a nested data-structure
            // […] write leading start-marker
            serialise<protocol, writeMetaInfo>(buffer, getAnnotatedMember(unwrapPointer(fieldValue)), field); // recursive call
            // […] write trailing stop-marker
        } else { // […] field is a (possibly annotated) primitive type → write (optional) field meta-data and primitive value
            IoSerialiser<protocol, writeMetaInfo>(buffer, field, getAnnotatedMember(unwrapPointer(fieldValue)));
        }
    });
}
```

… similar for deserialise function (albeit ~150 lines of code)

- primary optimisation goals:
  - read and process data only once, avoid if-else or jump branches → favours direct wire-format to object conversion
  - do field-name to index lookups already during compile-time (constexpr reflection/visitor pattern)

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

constexpr map<K,V> trick courtesy Jason Turner (C++ Weekly)

N.B std::map<K,V> and std::unordered_map<K,V> aren't constexpr

```
template<typename Key, typename Value, std::size_t size>
struct ConstExprMap {
    const std::array<std::pair<Key, Value>, size> data;

    [[nodiscard]] constexpr Value at(const Key &key) const {
        const auto itr = std::ranges::find_if(begin(data), end(data), [&key](const auto &v) {
            return v.first == key;
        });
        return (itr != end(data)) ? itr->second : throw std::out_of_range(fmt::format("key '{}' not found", key));
    }

    [[nodiscard]] constexpr Value at(const Key &key, const Value &defaultValue) const noexcept {
        auto itr = std::ranges::find_if(begin(data), end(data), [&key](const auto &v) { return v.first == key; });
        return (itr != end(data)) ? itr->second : defaultValue;
    }
};
```

… works well for smallish maps.

N.B. further optimisation potential: constexpr/compile-time sorting of keys (hard for strings)
→ opens option of binary search O(N) → O(log(N))

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<Number T> // catches all numbers
struct IoSerialiser<YaS, T> {
    static constexpr uint8_t getDataTypeId() { return yas::getDataTypeId<T>(); }
    constexpr static void    serialise(IoBuffer &buffer, FieldDescription auto const    &/*field*/, const T &value) noexcept {
        buffer.put(value);
    }
    constexpr static void deserialise(IoBuffer &buffer, FieldDescription auto const & /*field*/, T &value) noexcept {
        value = buffer.get<T>();
    }
};
```

5. user-level schema extensions

through 'Duck'-Typing Polymorphism

"If it walks like a duck and it quacks like a duck, then it must be a duck"

```
template<SerialiserProtocol protocol, typename T>
struct IoSerialiser {
    constexpr static uint8_t getDataTypeId() { return 0xFF; } // default value
    constexpr static void    serialise(IoBuffer    &/*buffer*/, FieldDescription auto const &field, const T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::serialise(IoBuffer&, field: '{}', type '{}' value: '{}')", /* … */ );
    }
    constexpr static void deserialise(IoBuffer & /*buffer*/, FieldDescription auto const &field, T &value) {
        throw ProtocolException("not implemented IoSerialiser<{}>::deserialise(IoBuffer&, field: '{}', type '{}' value: '{}')",  /* … */ );
    }
};

template<Number T> // catches all numbers
struct IoSerialiser<Json, T> {
    inline static constexpr uint8_t getDataTypeId() { return IoSerialiser<Json, OTHER>::getDataTypeId(); }
    constexpr static void           serialise(IoBuffer &buffer, FieldDescription auto const           &/*field*/, const T &value) {
        const auto  start  = buffer.size();
        auto            size   = buffer.capacity();
        auto            data   = reinterpret_cast<char *>(buffer.data());

        std::to_chars_result result;
        if constexpr (std::is_floating_point_v<T>) {
             result = std::to_chars(data + start, data + size, value, std::chars_format::scientific);
        } else {
             result = std::to_chars(data + start, data + size, value); // fall-back
        }

        if (result.ec != std::errc()) { throw ProtocolException("error({}) serialising number at buffer position: {}", result.ec, start); }
        buffer.resize(static_cast<size_t>(result.ptr - data)); // new position
    }
    constexpr static void deserialise(IoBuffer &buffer, FieldDescription auto const & /*field*/, T &value) {  /* […] */    }
};
```

5. user-level schema extensions

Example: IoSerialiser<YaS> wire-format

- Frame Header – written once (pretty standard):
  magic number (compatibility), protocol name ‘YAS\0’, major|minor|micro version
- Field Header – for each struct/class member field:
  - uint8_t: data type ID – fixed for default types, 0xFD→OTHER/custom
  - int32_t: unique field hashCode identifier ↔ N.B. performance bottleneck (will probably drop this)
  - int32_t: dataStart offset
  - int32_t: dataSize – *N.B. 'headerStart' + 'dataStart + dataSize' == start of next field header*
  - std::string: full field name
  - optional – *N.B. send for each REQ/REP, suppressed/send only once for PUB/SUB pair*
    - std::string physical field unit ↔ use of mp-units
    - std::string user-/application-specific field description
    - uint8_t external field modifier → used communicates protocol evolution
      - i.e. enum: RO, RW_DEPRECATED, RO_DEPRECATED, RW_PRIVATE, RO_PRIVATE, UNKNOWN
      - N.B. '_PRIVATE' == private/non-production API
  - *<actual data block starts here>*
  - <… data body …>

5. user-level schema extensions

Example: IoSerialiser<YaS> wire-format

- primitive types – int[8, 64]_t || float || double || bool || uint8_t
  via: `std::is_signed_v<RawType> || is_same_v<RawType, bool> || is_same_v<RawType, uint8_t>`
  - <straight x86_64 type> – preferred architecture/others need converter
    - N.B. dropped host/network since little-endian architectures dominate
- UTF-8 Strings, array, vector or other std container of primitives/strings
  - int32_t: size of vector N
  - N x [<type>]: vector elements/char
  - for strings: enforces trailing '\0'
- N-Dim arrays ↔ idea: follow-up C++23 std::mdspan<> concept
  - N_d x [<type>]: N_d-dim array storing the cardinality of each dimension
  - N x [<type>]: strided array storing the flat (dense) matrix
- maps ↔ composite of map size and arrays of key and value
- nested structs
  - uint8_t: START_MARKER
    - <… nested data body …>
  - uint8_t: END_MARKER
- optional custom types – essentially: server-/client need to agree/use the same definition, e.g.
  - std::string type name
  - <custom data format> user defined, …

5. user-level schema extensions

Example: IoSerialiser<YaS> wire-format

- primitive types – int[8, 64]_t || float || double || bool || uint8_t
  via: `std::is_signed_v<RawType> || is_same_v<RawType, bool> || is_same_v<RawType, uint8_t>`
  - <straight x86_64 type> – preferred architecture/others need converter
    - N.B. dropped host/network since little-endian architectures dominate
- UTF-8 Strings, array, vector or other std container of primitives/strings
  - int32_t: size of vector N
  - N x [<type>]: vector elements/char
  - for strings: enforces trailing '\0'
- N-Dim arrays ↔ idea: follow-up C++23 std::mdspan<> concept
  - N_d x [<type>]: N_d-dim array storing the cardinality of each dimension
  - N x [<type>]: strided array storing the flat (dense) matrix
- maps ↔ composite of map size and arrays of key and value
- nested structs
  - uint8_t: START_MARKER
    - <… nested data body …>
  - uint8_t: END_MARKER
- optional custom types – essentially: server-/client need to agree/use the same definition, e.g.
    - std::string type name
    - <custom data format> user defined, …

this where C++, meta-programming, and constexpr shines

10-fold SLOC reduction

example: IoSerialiser<YaS>

```cpp
#include <IoSerialiserYaS.hpp>

struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
ENABLE_REFLECTION_FOR(className, field1, field2, field3)  // needed for compile-time reflection until C++23/26
```

example: IoSerialiser<YaS>

```cpp
#include <IoSerialiserYaS.hpp>

struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
ENABLE_REFLECTION_FOR(className, field1, field2, field3)  // needed for compile-time reflection until C++23/26

int main() {
    className a{ 1, 0.5F, "Hello World!" };
    className b{ 1, 0.501F, "Γειά σου Κόσμε!" };


    diffView(std::cout, a, b); // convenience diff function

    opencmw::IoBuffer buffer;
    assert(a != b && "a & b should be unequal here");

    opencmw::serialise<opencmw::YaS>(buffer, a); // serialise 'a' into the byte buffer


    try { // de-serialise the byte buffer into 'b'
        opencmw::deserialise<opencmw::YaS, opencmw::ProtocolCheck::LENIENT>(buffer, b);
    } catch (const ProtocolException &e) {
        std::cout << "caught deserialisation exception: " << e.what() << std::endl;
    }
    assert(a == b && "a & b should be equal here"); // just checking
}
```

example: IoSerialiser<YaS>

```
#include <IoSerialiserYaS.hpp>

struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
ENABLE_REFLECTION_FOR(className, field1, field2, field3)  // needed for compile-time reflection until C++23/26

int main() {
    className a{ 1, 0.5F, "Hello World!" };
    className b{ 1, 0.501F, "Γειά σου Κόσμε!" };


    diffView(std::cout, a, b); // convenience diff function

    opencmw::IoBuffer buffer;
    assert(a != b && "a & b should be unequal here");

    opencmw::serialise<opencmw::YaS>(buffer, a); // serialise 'a' into the byte buffer


    try { // de-serialise the byte buffer into 'b'
        opencmw::deserialise<opencmw::YaS, opencmw::ProtocolCheck::LENIENT>(buffer, b);
    } catch (const ProtocolException &e) {
        std::cout << "caught deserialisation exception: " << e.what() << std::endl;
    }
    assert(a == b && "a & b should be equal here"); // just checking
}
```

Output:

```
diffView: className(
  0: int32_t                className::field1             = 1
  1: float_t                className::field2             = 0.5 vs. 0.501
  2: string                 className::field3             = Hello World! vs. Γειά σου Κόσμε!
 )
```

6. self-documented structures

more elaborate unit-test example

```
struct NestedDataY {
    Annotated<int8_t, length<metre>, "nested int8_t">                           annByteValue   = 11;
    Annotated<int16_t, si::time<second>, "custom description for int16_t">     annShortValue  = 12;
    Annotated<int32_t, NoUnit, "custom description for int32_t">               annIntValue    = 13;
    Annotated<int64_t, NoUnit, "custom description for int64_t">               annLongValue   = 14;
    Annotated<float, energy<gigaelectronvolt>, "custom description for float"> annFloatValue  = 15.0F;
    Annotated<double, mass<kilogram>, "custom description for double", RW>      annDoubleValue = 16.0;
    Annotated<std::string, NoUnit, "custom description for string">            annStringValue = std::string("nested string");
    Annotated<std::array<double, 10>, NoUnit>                                   annDoubleArray = std::array<double, 10>{ /*…*/ };
    Annotated<std::vector<float>, NoUnit>                                       annFloatVector = std::vector{ /*…*/ };
    Annotated<std::array<bool, 4>, NoUnit, "description for bool array!">      annBoolArray   = std::array<bool, 4>{ /*…*/ };
    auto operator<=>(const NestedDataY &) const = default;
};
ENABLE_REFLECTION_FOR(NestedDataY, annByteValue, annShortValue, annIntValue, annLongValue, annFloatValue, annDoubleValue,
annStringValue, annDoubleArray, annFloatVector, annBoolArray)

struct DataY {
    bool                                            boolValue        = false;
    int8_t                                          byteValue        = 1;
    int16_t                                         shortValue       = 2;
    int32_t                                         intValue         = 3;
    int64_t                                         longValue        = 4;
    float                                           floatValue       = 5.0F;
    double                                          doubleValue      = 6.0;
    std::string                                     stringValue      = "bare string";
    std::string const                               constStringValue = "unmodifiable string";
    std::array<double, 10>                          doubleArray      = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
    std::array<double, 10> const                    constDoubleArray = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
    std::vector<float>                              floatVector      = { 0.1F, 1.1F, 2.1F, 3.1F, 4.1F, 5.1F, /*…*/ };
    opencmw::MultiArray<double, 2>                  doubleMatrix{ { 1, 3, 7, 4, 2, 3 }, { 2, 3 } };
    NestedDataY                                     nestedData;
    Annotated<double, resistance<ohm>>              annotatedValue   = 0.1;
    std::map<std::string, std::string, std::less<>> map              = { { "key1", "value1" }, /*…*/ };
    std::map<std::string, std::string, std::less<>> smallMap         = { { "key1", "value1" } };

    bool                                            operator==(const DataY &) const = default;
};
ENABLE_REFLECTION_FOR(DataY, boolValue, byteValue, shortValue, intValue, longValue, floatValue, doubleValue, stringValue,
constStringValue, doubleArray, floatVector, /*doubleMatrix,*/ nestedData, annotatedValue, map, smallMap)
```

6. self-documented structures

example: IoSerialiser<YAML>

```
---
io_serialiser_yaml_test::DataY:
  boolValue: false                                                             # b
  byteValue: 1                                                                 # int8_t
  /* … */
  stringValue: "bare string"                                                   # string
  constStringValue: "unmodifiable string"                                      # string
  doubleArray: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9]                                  # array<double_t,10>
  floatVector: [0.1, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 8.1, 9.1, 9.1]              # vector<float_t>
  nestedData:
    annByteValue: 11                                                           # int8_t    - [m] - nested int8_t
    annShortValue: 12                                                          # int16_t   - [s] - custom description for int16_t
    annIntValue: 13                                                            # int32_t   - custom description for int32_t
    annLongValue: 14                                                           # int64_t   - custom description for int64_t
    annFloatValue: 15                                                          # float_t   - [GeV] - custom description for float
    annDoubleValue: 16                                                         # double_t  - [kg] - custom description for double
    annStringValue: "nested string"                                            # string    - custom description for string
    annDoubleArray: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9]                             # array<double_t,10>
    annFloatVector: [0.1, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 8.1, 9.1, 9.1]         # vector<float_t>
    annBoolArray: [true, false, true, true]                                    # array<b,4>      - description for bool array!
  # end - nestedData
  annotatedValue: 0.1                                                          # double_t  - [ohm]
  map:                                                                         # map<string,string>
    key1: "value1"
    key2: "value2"
    key3: "value3"
    key4: "value4"
    key5: "value5"
    key6: "value6"
  smallMap: {key1: "value1"}                                                   # map<string,string>
# end - io_serialiser_yaml_test::DataY
…
```

- **use-case: human-readable/-editable microservice config files (stored on GSI’s GitLab)**

6. self-documented structures

example: IoSerialiser<YAML>

```
---
io_serialiser_yaml_test::DataY:
  boolValue: false
  byteValue: 1
  /* … */
  stringValue: "bare string"
  constStringValue: "unmodifiable string"
  doubleArray: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
  floatVector: [0.1, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 8.1, 9.1, 9.1]
  nestedData:
    annByteValue: 11
    annShortValue: 12
    annIntValue: 13
    annLongValue: 14
    annFloatValue: 15
    annDoubleValue: 16
    annStringValue: "nested string"
    annDoubleArray: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
    annFloatVector: [0.1, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 8.1, 9.1, 9.1]
    annBoolArray: [true, false, true, true]
  # end - nestedData
  annotatedValue: 0.1
  map:
    key1: "value1"
    key2: "value2"
    key3: "value3"
    key4: "value4"
    key5: "value5"
    key6: "value6"
  smallMap: {key1: "value1"}
# end - io_serialiser_yaml_test::DataY
…
```

optional meta info

```
# b
# int8_t

# string
# string
# array<double_t,10>
# vector<float_t>
```

type unit user/server-side description

```
# int8_t    - [m] - nested int8_t
# int16_t   - [s] - custom description for int16_t
# int32_t   - custom description for int32_t
# int64_t   - custom description for int64_t
# float_t   - [GeV] - custom description for float
# double_t  - [kg] - custom description for double
# string    - custom description for string
# array<double_t,10>
# vector<float_t>
# array<b,4>      - description for bool array!

# double_t  - [ohm]
# map<string,string>
```

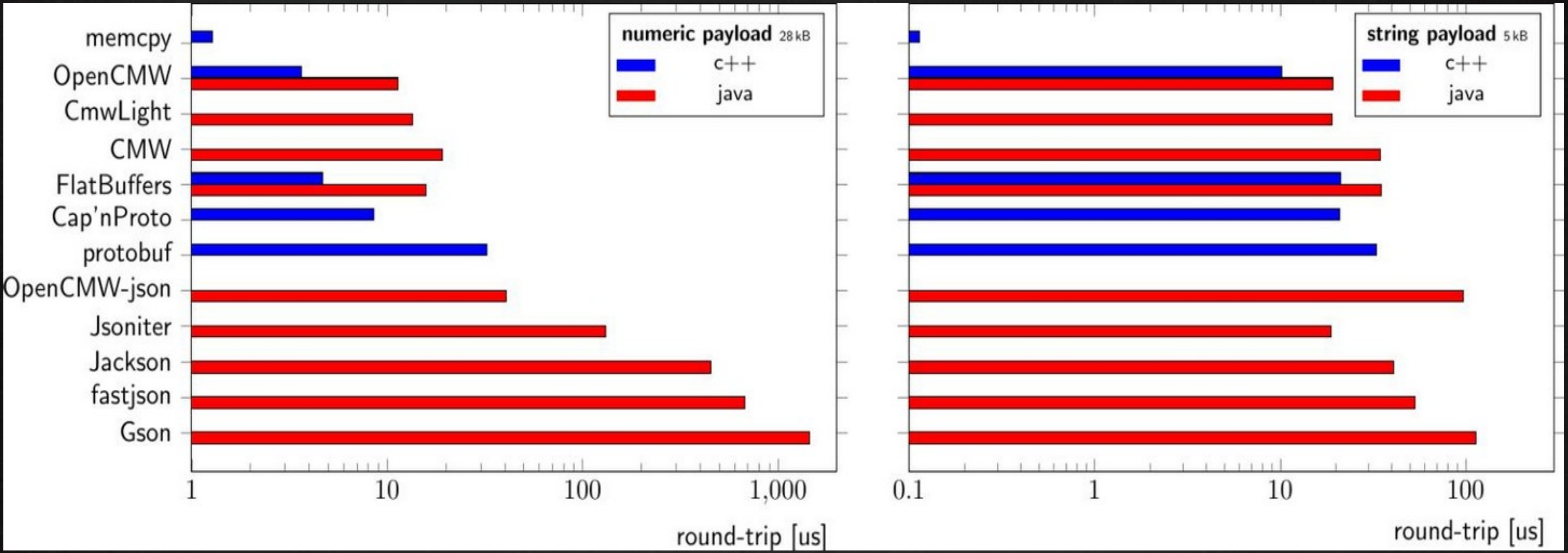
key: independent on and same PoCos for each wire-format

```
# map<string,string>
```

- **use-case: human-readable/-editable microservice config files (stored on GSI's GitLab)**

Serialiser performance

latency & bandwidths



C++ benchmark output:

```
┌─protocol─┬────────ALWAYS─────────┬────────LENIENT────────┬────────IGNORE─────────┐
│   YAML    │ 84.3 MB/s ±   8.1 MB/s│ 83.6 MB/s ± 427.6 kB/s│ 86.3 MB/s ± 539.8 kB/s│
│   Json    │283.2 MB/s ±   1.6 MB/s│283.0 MB/s ±   1.8 MB/s│287.0 MB/s ± 854.8 kB/s│
│   YaS     │  6.0 GB/s ±  33.0 MB/s│  6.3 GB/s ±  22.6 MB/s│  7.7 GB/s ±  47.9 MB/s│
│ CmwLight  │  8.0 GB/s ±  39.8 MB/s│  8.2 GB/s ±  24.9 MB/s│  9.3 GB/s ± 104.0 MB/s│
│           │                       │                       │                       │
└───────────┴───────────────────────┴───────────────────────┴───────────────────────┘
```

7. & 9. Overall Design

minimise code-bloat & free- and open-source

- lean-programming paradigm
  - removing wastes by design
    → improves performance through reduced L1/L2/L3 code cache sizes
  - minimises dependencies & maintenance overhead
  - improves likeliness of others to use, fix, and/or contribute
    - enabling factors: C++20, constexpr, meta-programming, compile-time reflection, unit-safety

- free- and open-source software w/o strings-attached
  - prerequisite for any scientific reproducibility, verifiability … or peer review
  - building a eco-system – op. integrated, exchangeable & transferable both across different labs as well as applications
  - public-private partnerships & “building people & systems”

References & Good Reads

- https://en.wikipedia.org/wiki/Lean_software_development
- Brian Goetz, "Towards Better Serialization", 2019
- Pieter Hintjens et al., "ZeroMQ's ZGuide on Serialisation" in 'ØMQ - The Guide', 2020
- Google's own Protobuf Serialiser
- Google's own FlatBuffer Serialiser
- Implementing High Performance Parsers in Java
- Is Protobuf 5x Faster Than JSON? (Part 1, Part 2) and reference therein

That's all

Questions? Feedback?

The King is conducting a survey – how do you feel about user feedback?
Oh, I can't complain.

Appendix

Serialiser performance

test-class

```
struct TestDataClass {
    // basic data types
    bool   bool1;
    bool   bool2;
    int8_t byte1;
    int8_t byte2;
    char   char1;
    char   char2;
    short  short1;
    short  short2;
    int    int1;
    int    int2;
    long   long1;
    long   long2;
    float  float1;
    float  float2;
    double double1;
    double double2;
    string string1;
    string string2;

    // 1-dim arrays
    vector<char>    boolArray;
    vector<int8_t> byteArray;
    vector<int16_t> shortArray;
    vector<int32_t> intArray;
    vector<int64_t> longArray;
    vector<float>   floatArray;
    vector<double>  doubleArray;
    vector<string>  stringArray;

    // generic n-dim arrays - N.B. striding-arrays: low-level format is the same except of 'nDimension' descriptor
    array<int, 3>   nDimensions;
    vector<char>    boolNdimArray;
    vector<int8_t> byteNdimArray;
    vector<int16_t> shortNdimArray;
    vector<int32_t> intNdimArray;
    vector<int64_t> longNdimArray;
    vector<float>   floatNdimArray;
    vector<double>  doubleNdimArray;

    unique_ptr<TestDataClass> nestedData;// nested class
};
ENABLE_REFLECTION_FOR(TestDataClass, bool1, bool2, …)
```

Compile-Time Reflection

Example based upon:https://github.com/veselink1/refl-cpp (C++17)

```
struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
```

Compile-Time Reflection

Example based upon:https://github.com/veselink1/refl-cpp (C++17)

```
struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
ENABLE_REFLECTION_FOR(className, field1, field2, field3)  // needed until C++23/26
```

Compile-Time Reflection

Example based upon:https://github.com/veselink1/refl-cpp (C++17)

```
struct className {
    int         field1;
    float       field2;
    std::string field3;
    bool operator==(const className &) const = default;
};
ENABLE_REFLECTION_FOR(className, field1, field2, field3)  // needed until C++23/26

// here with additional unit type-safety checks (see also: constexpr, strict type-checking & mp-units)
```

```
using opencmw::Annotated;
struct otherClass {
   Annotated<float, thermodynamic_temperature<kelvin>, "device specific temperature">        temperature      = 23.2F;
   Annotated<float, electric_current<ampere>, "this is the current from ...">                current          = 42.F;
   Annotated<float, energy<electronvolt>, "SIS18 energy at injection before being captured"> injectionEnergy  = 8.44e6F;
   std::unique_ptr<NestedClassType>                                                          nested;
   // [..]

   // just good common practise to define some operators
   bool operator==(const otherClass &) const = default;
};
ENABLE_REFLECTION_FOR(otherClass, temperature, current, injectionEnergy, nested)
```