GNU Radio 4.0: Standing on the Shoulders of Giants

An Overview of New Features and Significant Enhancements

Josh Morman[1], Derek Kozel[1], Ralph J. Steinhagen[2]

on behalf of: the GR Architecture Team, Björn Balazs[3], Giulio Camuffo[3], Ilya Doroshenko[3], Alexander Krimm[2], Semën Lebedev[2], Ivan Čukić[3], Matthias Kretz[2], Frank Osterfeld[3], ...

[1] GNU Radio 4.0 (lead)
[2] FAIR – Facility for Anti-Proton and Ion Research & GSI, Darmstadt, Germany
[3] KDAB Berlin, Germany

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Modernisation Goals

GNU Radio organically grew the past 20 years ...

photos courtesy: https://fieldertree.com/
https://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants

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Modernisation Goals

GNU Radio organically grew the past 20 years ...

… GR 4.0 opportunity: preserve what is good, prune what is unhealthy to keep the project growing and maintainable ~~for another 20 years~~

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Modernisation Goals

simplify onboarding for new contributors to participate/contribute more effectively

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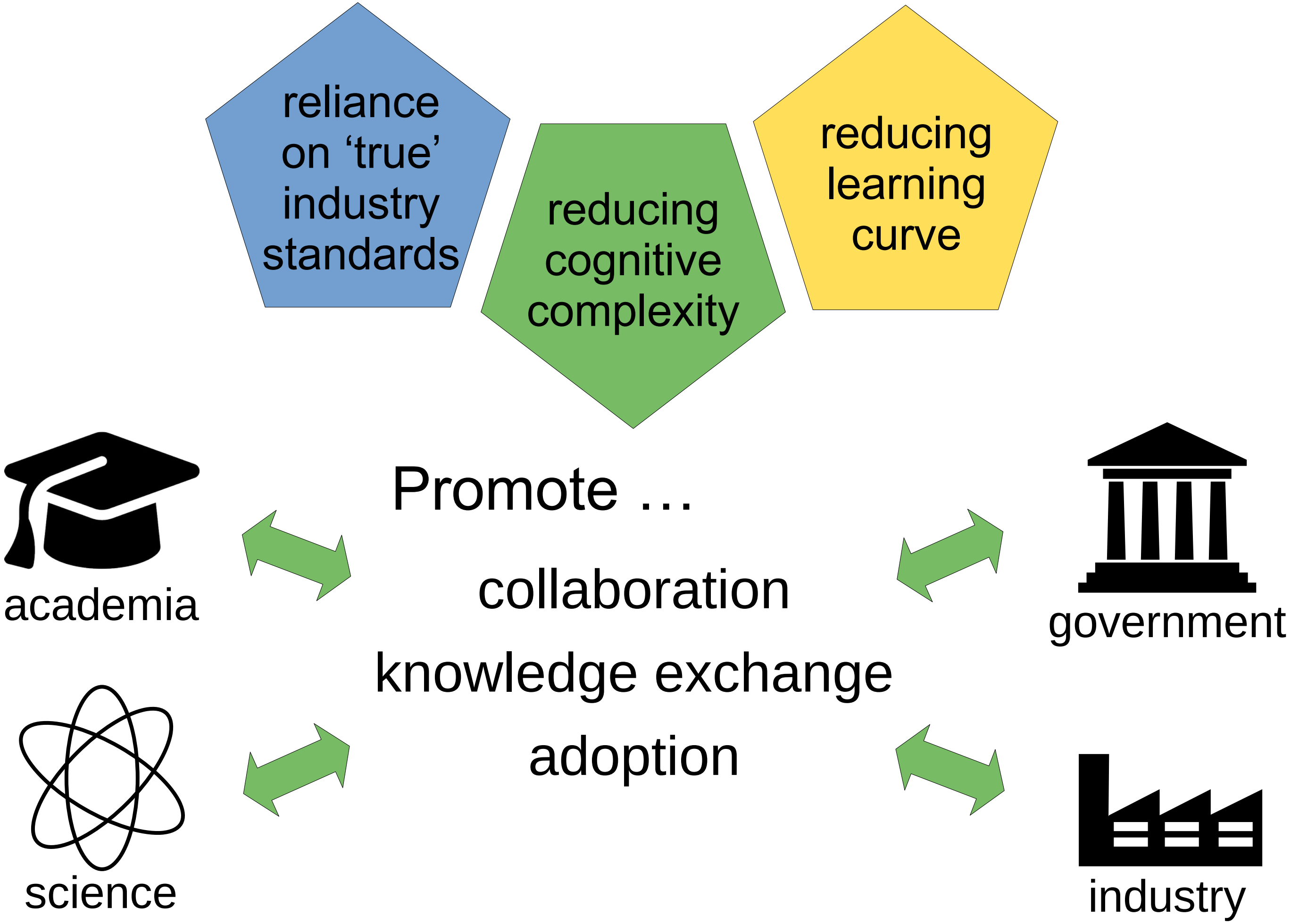

Modernisation Goals

improve performance, industrial integration+deployment

1. **Preserve and Grow the existing diverse GR Ecosystem.**
   - thin Python interface over C++ API
   - avoid Python-only implementations (except OOT modules)
   - swappable runtime components (both in and out of tree)
   - simplified block development: get block developers to "insert code here" without lots of boilerplate or complicated code
2. **Clean- and Lean Code-Base Redesign**
3. **Performance Optimisations**
4. **Tag-Based Timing System Integration** (White Rabbit, GPS, SW-based etc.)
5. **Advanced Processing Features**
6. **Broaden Cross-Platform Support** (including WebAssembly)
7. **User-pluggable Work Scheduler Architecture**
8. **Overall Project Direction**

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – “Hello GNU Radio World!”

```cpp
struct BasicMultiplier : public node<BasicMultiplier> {
  IN<float>   in;
  OUT<float>  out;
  float       scaling_factor = static_cast<float>(1);



  [[nodiscard]] constexpr float
  process_one(const float &a) const noexcept {
      return a * scaling_factor;
  }
};

ENABLE_REFLECTION_FOR(BasicMultiplier, in, out, scaling_factor);
```

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Key Take-Aways:

- **Simplified Block Development**: stand-alone creation is more intuitive. Code is the single source of truth.
  Feedback? Let's discuss!
- **Efficient Functional Unit Testing**: directly test blocks without embedding in flow-graphs
  - offer three basic (optional) API variants: sample-by-sample, chunked, or arbitrary processing (i.e. '`work(…)`') function
- **Compiler-Optimised Interface**: Type-strictness and constraints help w.r.t. efficient compiler optimisations
- **Early Error Detection**: most issues caught during compile time, reducing errors and debugging during run-time

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – with SIMD acceleration

```
template<typename T>
requires (std::is_arithmetic<T>())
struct BasicMultiplier : public node<BasicMultiplier<T>> {
  IN<T>        in;
  OUT<T>       out;
  T            scaling_factor = static_cast<T>(1);


  template<t_or_simd<T> V> // → intrinsic SIMD support
  [[nodiscard]] constexpr V
  process_one(const V &a) const noexcept {
      return a * scaling_factor;
  }
};
```

```
ENABLE_REFLECTION_FOR_TEMPLATE_FULL((typename T),(BasicMultiplier<T>), in, out, scaling_factor);
```

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – classic bulk operation I/II

```
template<typename T>
requires (std::is_arithmetic<T>())
struct BasicMultiplier : public node<BasicMultiplier<T>> {
  IN<T>       in;
  OUT<T>      out;
  T           scaling_factor = static_cast<T>(1);



  void // alternate interface
  process_bulk(std::span<const T> in, std::span<T> out) {
      std::ranges::transform(in, out.begin(), [sf = scaling_factor](const T& val) {
        return val * sf;
    });
  }
};

ENABLE_REFLECTION_FOR_TEMPLATE_FULL((typename T), (BasicMultiplier<T>),in,out,scaling_factor,context);
```

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```

Fun Fact (aka. beware of ‘premature optimisations’):

Benchmarking proved that using ‘`process_one(…)`’ is numerically more performant than ‘`process_bulk(…)`’

rationale: locality, reduced scope that can be better exploited by the compiler and L1/L2/L3 CPU cache.

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"insert code here" without lots of boilerplate or complicated code – classic bulk operation II/III

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struct BasicMultiplier : public node<BasicMultiplier<T>> {
  IN<T>         in;
  OUT<T>        out;
  T             scaling_factor = static_cast<T>(1);


  void // alternate interface with variable amount of input and output consumed
  process_bulk(ConsumableSpan auto& in, PublishableSpan auto& out) const noexcept {
      // [..] user-defined processing logic [..]
      in.consume(3UL);  // consume 3 samples
      out.publish(2UL); // publish 2 samples → effectively a 3:2 re-sampler
  }
};

ENABLE_REFLECTION_FOR_TEMPLATE_FULL((typename T), (BasicMultiplier<T>),in,out,scaling_factor,context);
```

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – Decimator & Interpolator

```
template<typename T>
requires (std::is_arithmetic<T>())
struct Resampler : public node<Resampler<T>, PerformDecimationInterpolation, PerformStride> {
  IN<T>       in;
  OUT<T>      out;


  void // ‘in’ and ‘out’ matched N x numerator & N x denominator samples
  process_bulk(std::span<const T> in, std::span<T> out) const noexcept {
      // [..] user-defined re-sampling logic [..]
  }
};
ENABLE_REFLECTION_FOR_TEMPLATE_FULL((typename T), (Resampler<T>), in, out);
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1. Preserve and Grow the existing diverse GR Ecosystem

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optional NTTP parameters → "only-pay-for-what you use"

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[..] user application code:

```
graph flow; // flow-graph object owning the blocks/connections
auto &block = flow.make_node<Resampler<float>>({“numerator”, 1024UL}, {“denominator”, 1UL});
```

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block.settings().set({"stride", 10'000UL}); // std::map<std::string, pmt_t> interface
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// alternate direct interface
block.stride =  10'000UL;
block.update_active_parameters(); // N.B. synchronises PMT-map representation
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```

Shout-out to: Semën Lebedev for fleshing this out and covering most corner cases

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – "Hello GNU Radio World!" V2

```
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struct BasicMultiplier : public node<BasicMultiplier<T>> {
  IN<T>       in;
  OUT<T>      out;
  T           scaling_factor = static_cast<T>(1);
  std::string context;     // ↔ multiplexing settings




  template<t_or_simd<T> V>
  [[nodiscard]] constexpr V
  process_one(const V &a) const noexcept {
      return a * scaling_factor;
  }
};

ENABLE_REFLECTION_FOR_TEMPLATE_FULL((typename T),(BasicMultiplier<T>),in,out,scaling_factor,context);
```

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – Settings Management

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template<typename T>
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  T           scaling_factor = static_cast<T>(1);
  std::string context;     // ↔ multiplexing settings

  void settings_changed(const property_map &old, const property_map &new) {
    // optional function that is called whenever settings change
  }

  template<t_or_simd<T> V>
  [[nodiscard]] constexpr V
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  [[nodiscard]] constexpr V
  process_one(const V &a) const noexcept {
      return a * scaling_factor;
  }
};
```

two settings update mechanisms:

a) via thread-safe getter/setter (std::map<string, pmt_t>)

b) via streaming tags
N.B. 'process_XXX' is (default) invoked with the first sample after settings have been applied

c) via async message port (std::map<string, pmt_t>)

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FAIR GSI

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c) via async message port (std::map<string, pmt_t>)

Shout-out to: John Sallay for providing the new PMT library extension (pls. buy him a beer).

FAIR GSI

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – FIR pre-production code

```
template<typename T>
requires std::floating_point<T>
struct fir_filter : node<fir_filter<T>, Doc<R""(
@brief Finite Impulse Response (FIR) filter class

The transfer function of an FIR filter is given by:
H(z) = b[0] + b[1]*z^-1 + b[2]*z^-2 + ... + b[N]*z^-N
)"">> {
    IN<T>                in;
    OUT<T>               out;
    std::vector<T>       b{}; // feedforward coefficients
    history_buffer<T> inputHistory{ 32 };

    void
    settings_changed(const property_map & /*old_settings*/, const property_map &new_settings) noexcept {
        if (new_settings.contains("b") && b.size() >= inputHistory.capacity()) {
            inputHistory = history_buffer<T>(std::bit_ceil(b.size()));
        }
    }

    constexpr T
    process_one(T input) noexcept {
        inputHistory.push_back(input);
        return std::inner_product(b.begin(), b.end(), inputHistory.rbegin(), static_cast<T>(0));
    }
};
```

1. Preserve and Grow the existing diverse GR Ecosystem

"insert code here" without lots of boilerplate or complicated code – IIR pre-production code

```
template<typename T, IIRForm form = std::is_floating_point_v<T> ? IIRForm::DF_II : IIRForm::DF_I>
requires std::floating_point<T>
struct iir_filter : node<iir_filter<T, form>, Doc<R""(
@brief Infinite Impulse Response (IIR) filter class

b are the feed-forward coefficients (N.B. b[0] denoting the newest and n[-1] the previous sample)
a are the feedback coefficients
)"">> {
  IN<T>              in;
  OUT<T>             out;
  std::vector<T>     b{ 1 }; // feed-forward coefficients
  std::vector<T>     a{ 1 }; // feedback coefficients
  history_buffer<T> inputHistory{ 32 };
  history_buffer<T> outputHistory{ 32 };

  void
  settings_changed(const property_map & /*old_settings*/, const property_map &new_settings) noexcept {
    // [..] adjust history buffer sizes in case filters are changed
  }

  [[nodiscard]] T
  process_one(T input) noexcept {
    if constexpr (form == IIRForm::DF_I) {
      // y[n] = b[0] * x[n]   + b[1] * x[n-1] + ... + b[N] * x[n-N]
      //      - a[1] * y[n-1] - a[2] * y[n-2] - ... - a[M] * y[n-M]
      inputHistory.push_back(input);
      const T output = std::inner_product(b.begin(), b.end(), inputHistory.rbegin(), static_cast<T>(0))       //feed-forward
                     - std::inner_product(a.begin() + 1, a.end(), outputHistory.rbegin(), static_cast<T>(0)); //feedback path
      outputHistory.push_back(output);
      return output;
  } else { /* handle other IIR forms */ }
};
```

FAIR GSI

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  void
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  [[nodiscard]] T
  process_one(T input) noexcept {
    if constexpr (form == IIRForm::DF_I) {
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```

Note for the eagle-eyed: this is not your dad's C/C++98 ...

- primarily use STD-only C++20 (& compatible header-only C++26 libs) for enhanced performance and brevity
  N.B. no external platform specific dependencies ↔ portability
- driven/limited by libc++ implementation for WASM compatibility
  (N.B. MSVC & gcc's stdlibc++ are both more advanced)
- embrace modern C++ while avoiding overly bleeding-edges

Great CppCon 2022 talk by Daniela Engert (YouTube, ~1h):
[Contemporary C++ in Action]()

1. Preserve and Grow the existing diverse GR Ecosystem

Not a real concern … end-user Python & C++ top-level block API

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Not a real concern … end-user Python & C++ top-level block API

non-issues – keep as is:

```python
from gnuradio import gr, module_x, module_y

fg = flowgraph()

b1 = module_x.block_a_f(...)
b2 = module_y.block_b_f(...)
b3 = module_y.block_c_f(...)

fg.connect([b1, b2, b3])
# or fg.connect(b1, "port_name", b2, "port_name")
# or fg.connect(b1, 0, b2, 0)

fg.start()
fg.wait()
```

```python
class myblock : gr.block
  def __init__(*args, **kwargs):
    gr.block.__init__(...)


  def work(wio):
    # get np arrays from input ports
    # get mutable np arrays output ports

    # produce and consume

    return gr.work_return_t.OK
```

1. Preserve and Grow the existing diverse GR Ecosystem

Not a real concern … end-user Python & C++ top-level block API

Your Python-User Feedback is appreciated:

given the choice of a possible green-field re-design, do you prefer to have …

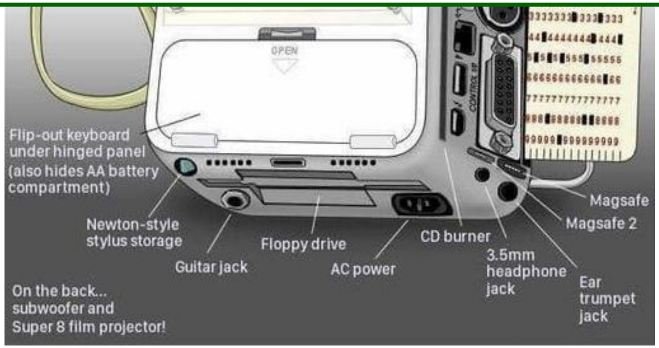
a) *the same interface as GR 3.X i.e. full access to all nooks and grannies of the full ‘`work(wio)`’ function?*
   - *possible, but high(er) core lib maintenance costs because of the various corner cases (↔ status quo)*

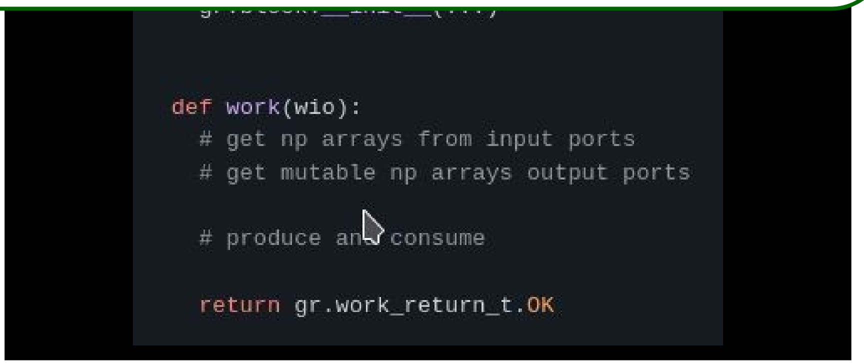
b) *the reduced equivalent of the ‘`process_one(…)`’ and ‘`process_bulk(…)`’ function?*
   - *reduced ‘attack-surface’ and easier/more flexible core lib maintenance*
   - *getting a better/easier interface for the 90% use case*

c) *none … e.g. I roll my own Python (pybind11, pypy, …), Java, Rust, etc. bindings*

d) *other …*

Please get in contact with the GR Architecture Team! It’s an Open Design!





Modernisation Goals

improve performance, industrial integration+deployment

1. Preserve and Grow the existing diverse GR Ecosystem.

2. Clean- and Lean Code-Base Redesign

- favour ‘composition’ over ‘inheritance’
- boosts maintainability and adaptability
- preserve tried-and-tested functionalities

3. Performance Optimisations
4. Tag-Based Timing System Integration
5. Advanced Processing Features
6. Broaden Cross-Platform Support
7. User-pluggable Work Scheduler Architecture
8. Overall Project Direction

Software must be adaptable to frequent changes

Meta-View on Software Design and GNU Radio

Software must be adaptable to frequent changes

- few are library developers
- more are application developers, i.e. users of the library
- most are application users

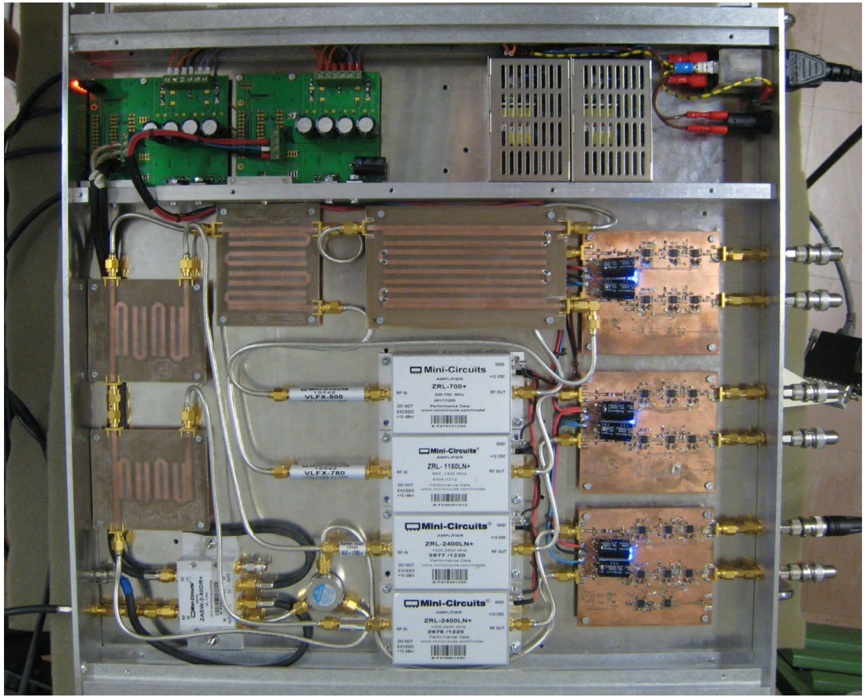
- all need to know ‘what’, ‘when’ and ‘where’ functionalities are implemented
  - common terminology – remain mindful about non-RF engineers and applications
    - aim: intuitive design before domain-language before documentation of concepts
  - common understanding of dependencies and interfaces
    - directed flow-graphs are great low-/high-level representations (‘mechanical sympathy’)
    - aim for the rest: present C++ STD → C++ Core Guidelines → C++ Best Practices*, …

*e.g. “Make Your API Hard To Use Wrong”, Scott Meyers, IEEE Software, July/August 2004

Meta-View on Software Design and GNU Radio

Software must be adaptable to frequent changes

- mechanical sympathy – why GR flow-graphs resonate well with RF engineers



full-range
0.4 GHz
0.8 GHz
1.2 GHz
1.6 GHz
full-range

Δ-Signal

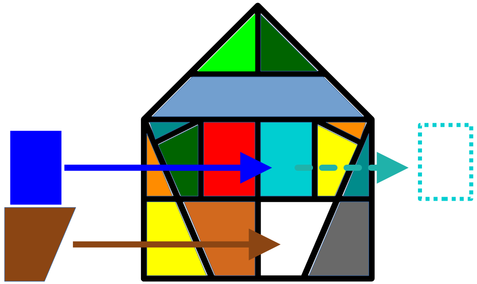
2. Clean- and Lean Code-Base Redesign

favour ‘composition’ over ‘inheritance’

- low-level library: ‘what’, ‘when’ and ‘where’ functionalities are implemented
  - safe, secure and better performance @ IO- and memory latency & bandwidths limits
    - only pay for what you use (aka. ‘zero-overhead principle’)
    - compile-time type-safety & concepts are overhead free ↔ virtual inheritance & RTTI aren’t
  - modern, lean-and-clean support of exchangeability & extendability through 'composition'

→ a) stronger separation-of-concern, transparent & ‘intuitive’ design*

→ b) light-weight, minimal, reduced to strictly-needed API & open for user-extensions



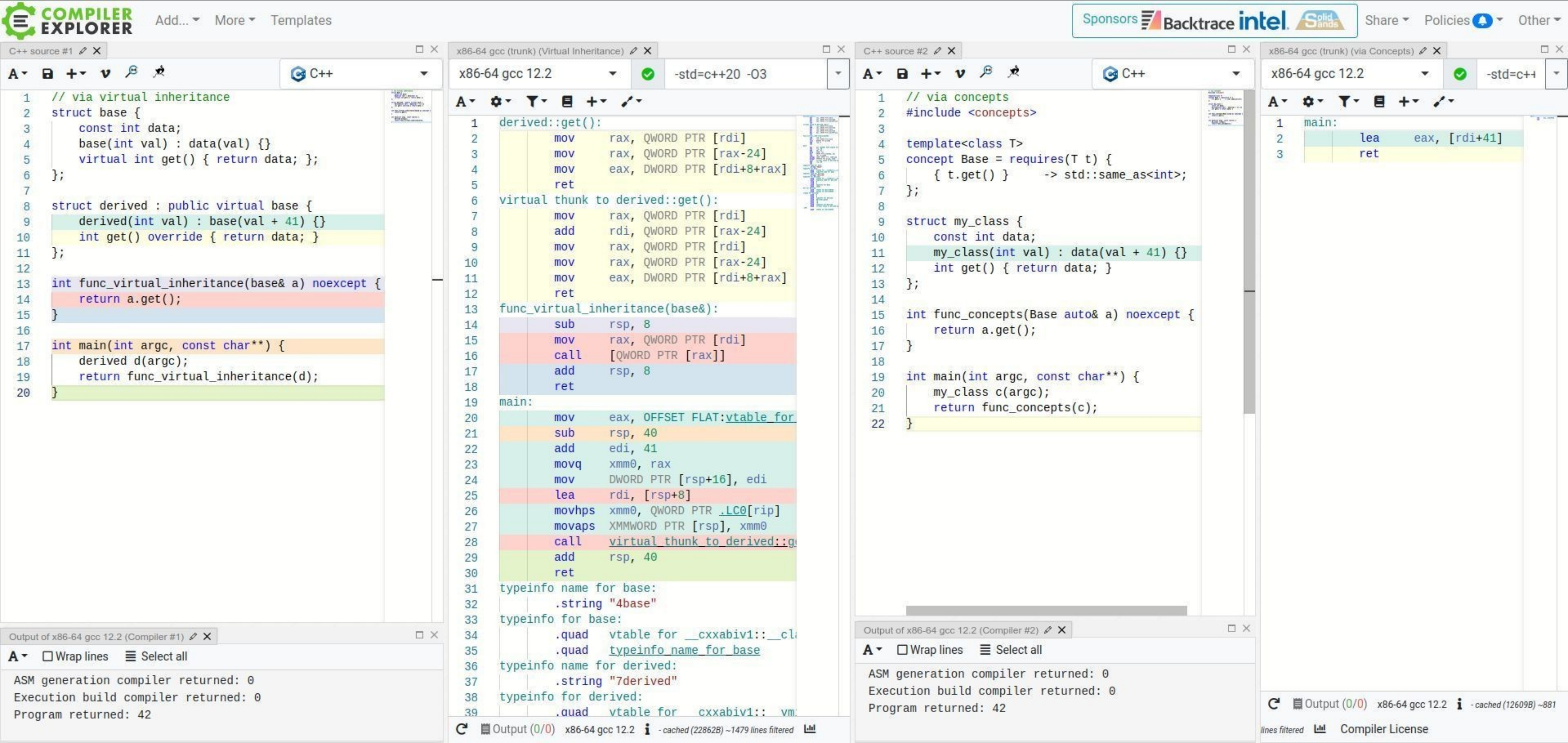
traditional (prescriptive) frameworks: user implements stubs
limited options to exchange or to extend

modular library: user can opt-in what to use and what is needed
...free to extend, modify, synthesis new ideas

*from a perspective of novice/new users with some RF, signal-processing, computer-science background

2. Clean- and Lean Code-Base Redesign

virtual inheritance vs. strict typing & concepts: https://compiler-explorer.com/z/fe5Khcxfv



2. Clean- and Lean Code-Base Redesign

strict typing & concepts – block implementation as the single source of truth derive

… can be used to generate Python bindings, code & UI documentation, provide UI meta information, further static reflection options, etc.

```
template<typename T>
requires (std::is_arithmetic<T>())
struct TestBlock : public node<TestBlock<T>, BlockingIO<true>, TestBlockDoc, SupportedTypes<float, double>,
Doc<R""(
some test doc documentation -- may use mark down, references etc. -- and can be read-out programmatically
// optional future extension:
// use existing input/output port information and constraints for additional documentation
)"">> {
    IN<T>        in;
    OUT<T>       out;
    A<T, "scaling factor", Visible, Doc<"y = a * x">, Unit<"As">> scaling_factor = static_cast<T>(1);
    A<std::string, "context information", Visible>              context;
    // ...
};
```

2. Clean- and Lean Code-Base Redesign

strict typing & concepts – block implementation as the single source of truth derive

… can be used to generate Python bindings, code & UI documentation, provide UI meta information, further static reflection options, etc.

Printout example:

```
# fair::graph::setting_test::TestBlock<float>
some test doc documentation -- may use mark down, references etc. -- and can be read-out programmatically
// optional future extension:
// use existing input/output port information and constraints for additional documentation


**BlockingIO**
i.e. potentially non-deterministic/non-real-time behaviour_

**supported data types:**0:float 1:double
**Parameters:**
float       scaling_factor       - annotated info: scaling factor unit: [As] documentation: y = a * x
std::string context              - annotated info: context information unit: [] documentation:
signed int  n_samples_max_
float       sample_rate_


~~Ports:~~ //[..]
```

Modernisation Goals

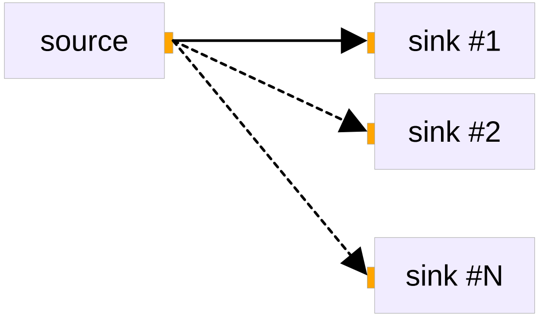
improve performance, industrial integration+deployment

1. Preserve and Grow the existing diverse GR Ecosystem.
2. Clean- and Lean Code-Base Redesign
3. **Performance Optimisations**
   - high-performance, type-strict IO buffers
   - zero-overhead for graphs known at compile-time
   - out-of-the-box hardware acceleration (SIMD, GPU, etc.)
   - optimise linear flow dependency sub-graphs (e.g. avoid/minimise need for buffers)
4. Tag-Based Timing System Integration
5. Advanced Processing Features
6. Broaden Cross-Platform Support
7. User-pluggable Work Scheduler Architecture
8. Overall Project Direction

3. Performance Optimisations

new high-performance, type-strict IO buffers **– Possible Use-Cases**

Fan-Out:



- multiple observer
- classic GR flow-graph use

3. Performance Optimisations

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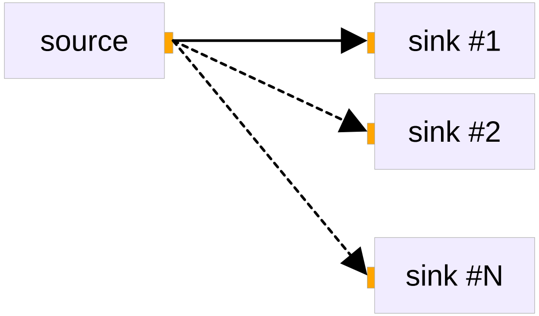

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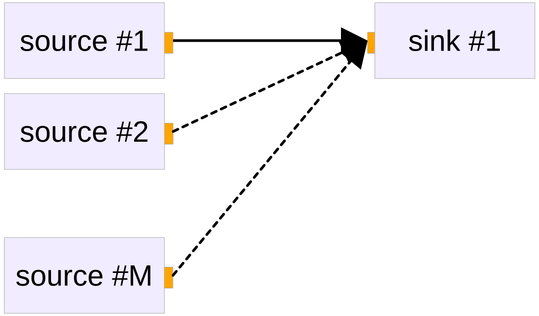

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- message passing
- decoupling between user-vs. real-time worker threads, e.g.
  - PMT block property updates from stream tags & user-thread

3. Performance Optimisations

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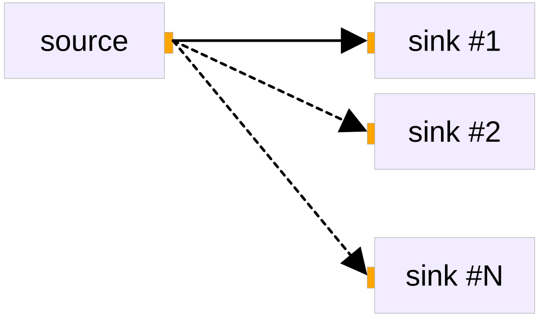

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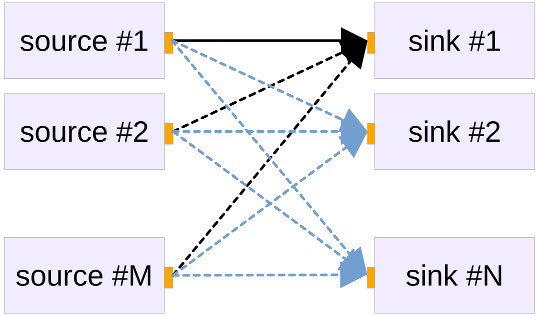

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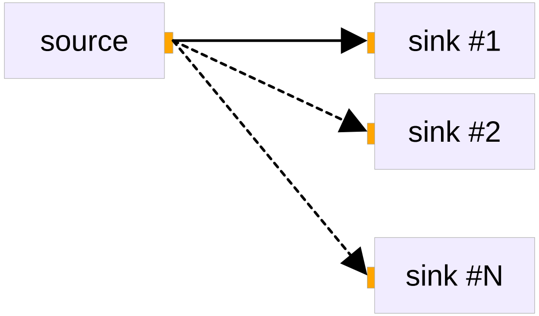

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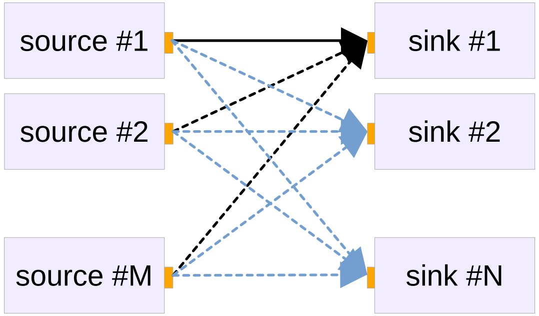

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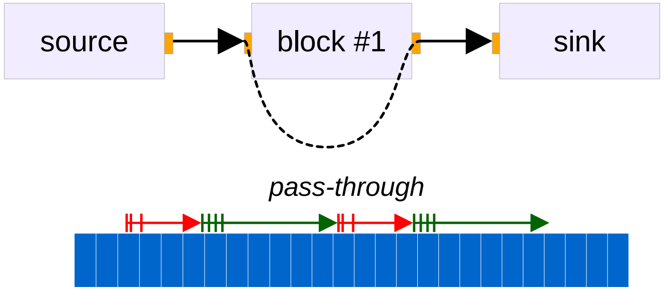

- cascaded reader/writer sharing same buffer → minimises copying
- good for blocks that monitor and rarely modify data

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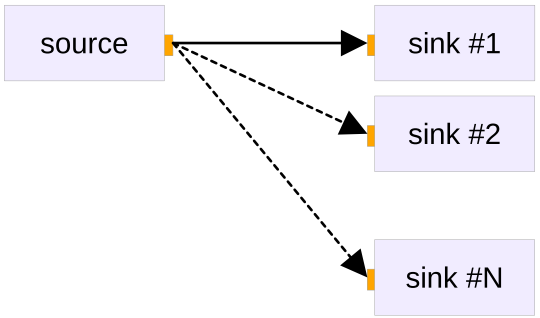

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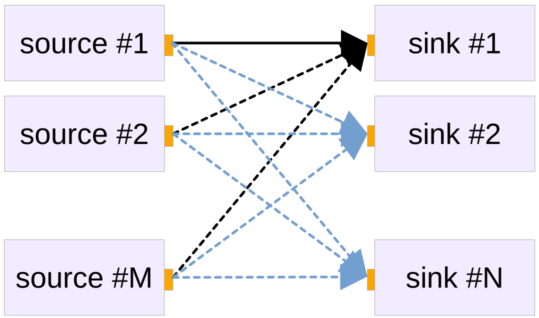

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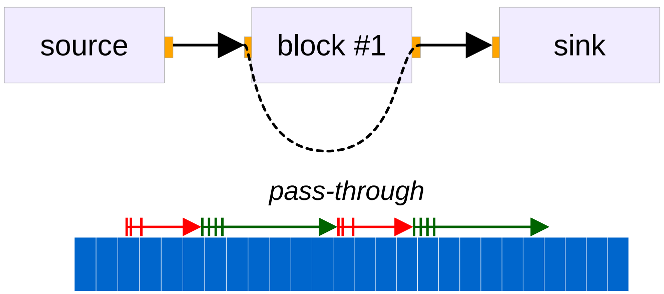

- cascaded reader/writer sharing same buffer
  → minimises copying
- good for blocks that monitor and rarely modify data

Important (hopefully positively perceived) changes:

- *type-strictness: new circular_buffer can propagate any type i.e. fundamentals but notably also aggregate types → e.g. DataSet<T>*
- *simplified async message and sync stream handling (i.e. the same)*

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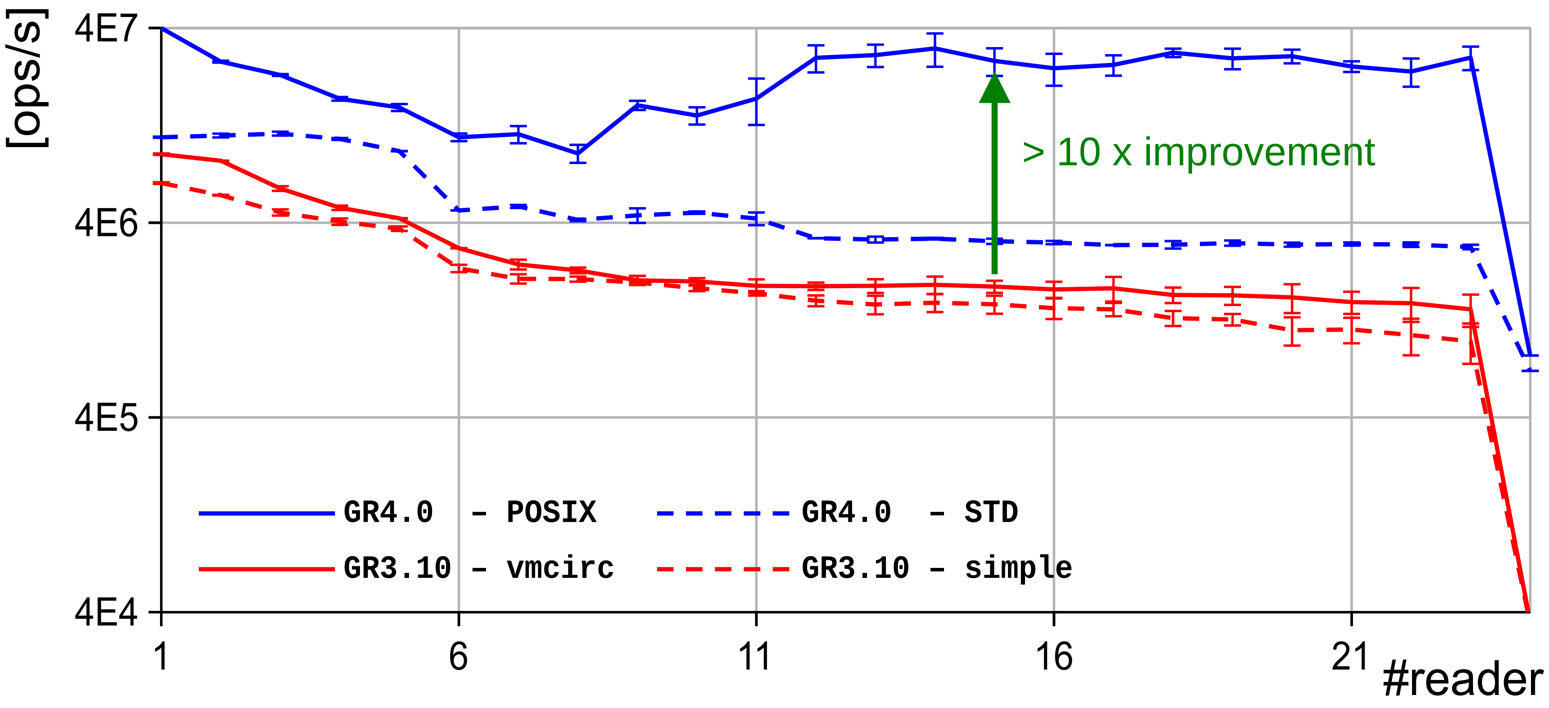
3. Performance Optimisations

high-performance, type-strict IO buffers



N.B. test scenario on equal footing
but absolute values could be improved
through better wait/scheduling strategies

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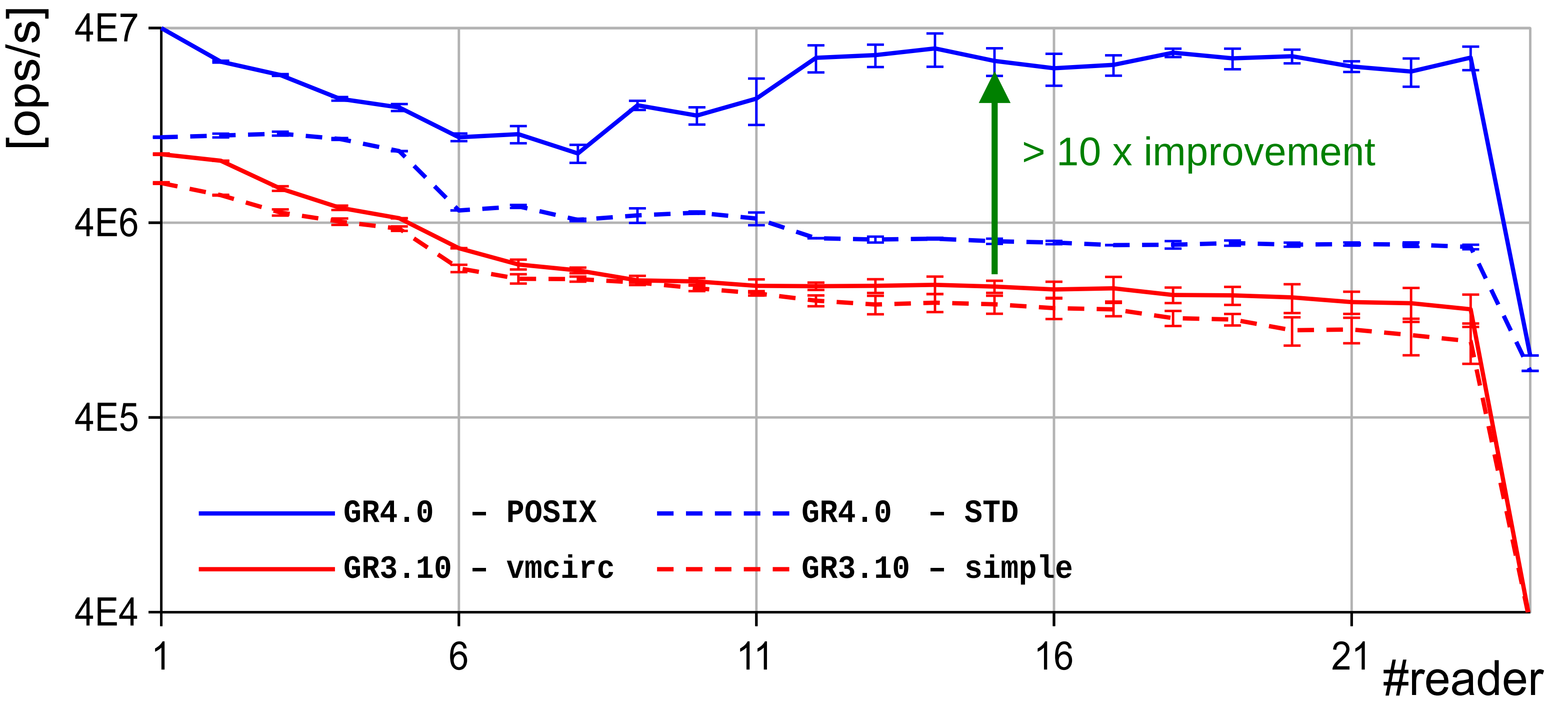

main key-ingredients:

- *made new circular_buffer<T> lock-free (using atomic CAS paradigm)*
- *strict typing & `constexpr`*
  → enables better compiler optimisation and L1/L2/L3 cache locality

N.B. test scenario on equal footing but absolute values could be improved through better wait/scheduling strategies

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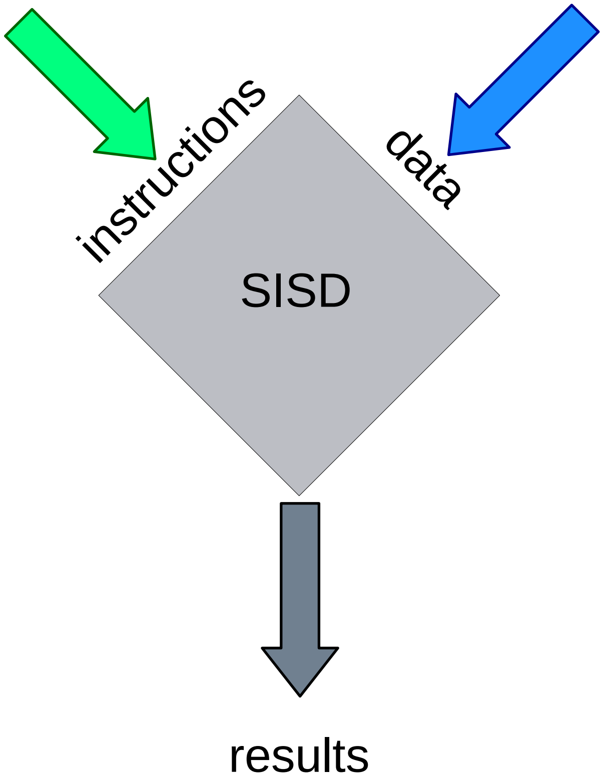
Performance Optimisations

out-of-the-box ‘Single Instruction, Multiple Data’ (SIMD) acceleration



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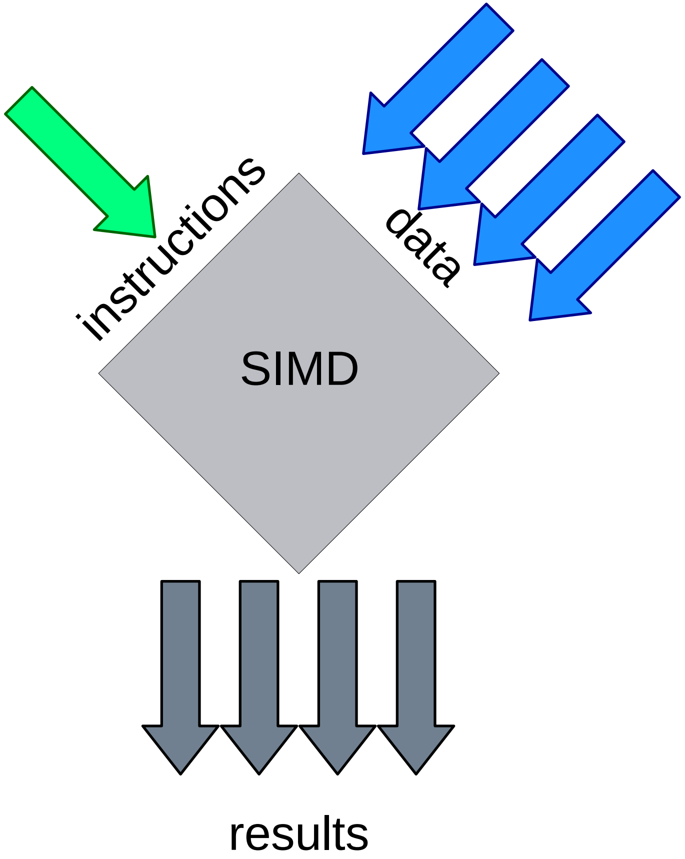

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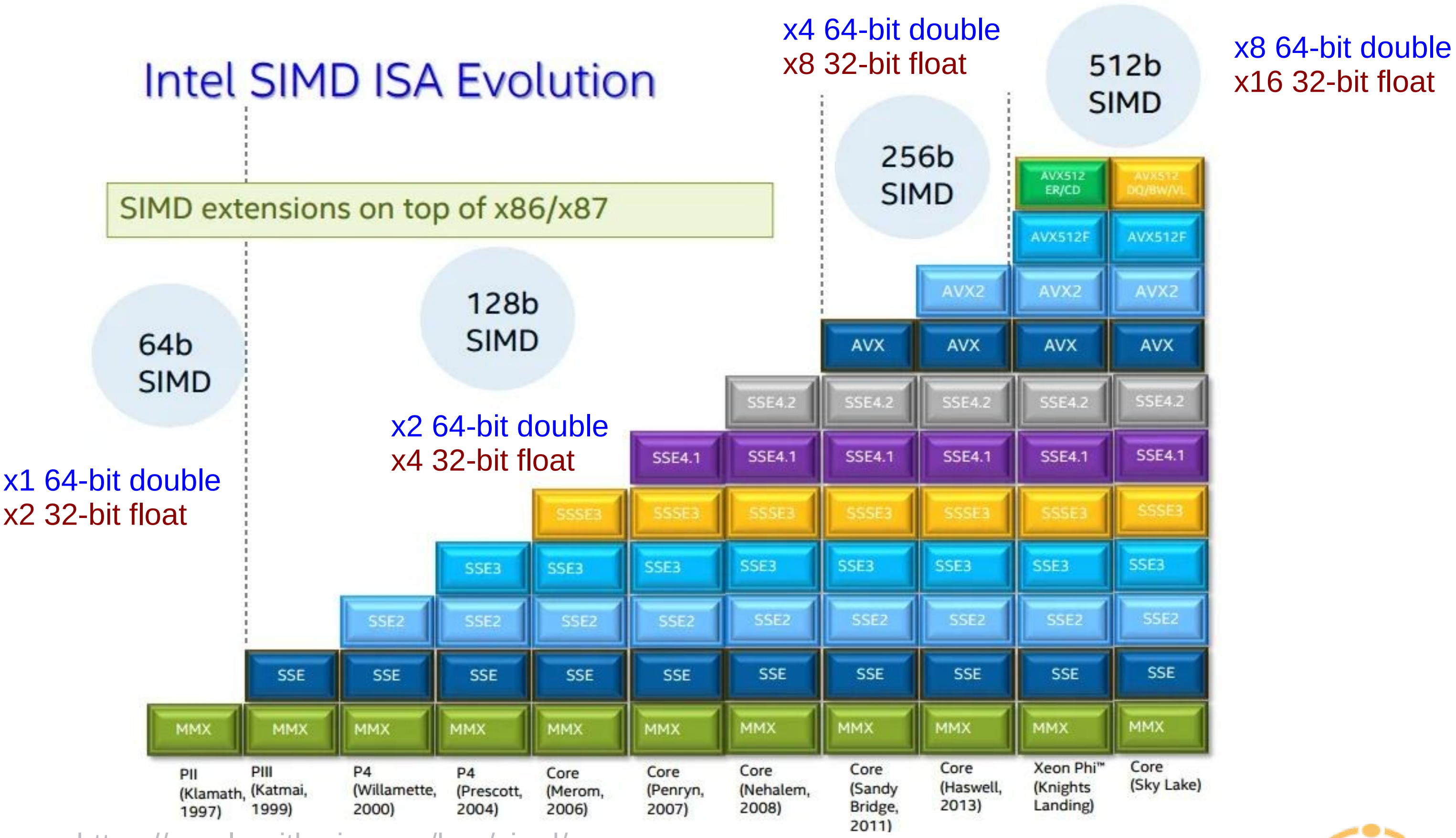

https://en.algorithmica.org/hpc/simd/

Performance Optimisations

out-of-the-box 'Single Instruction, Multiple Data' (SIMD) acceleration

SIMD: 'Single Instruction, Multiple Data'

- utilise all parallelism per CPU core
  (N.B. code often utilises only ~10% of the CPU die!!)
- more efficient use of memory bandwidth (and caches)
- reduces latency ↔ real-time systems
- improves efficiency and FLOP/power ratio
- portable & intuitive design of data-parallel blocks
- C++ dev can focus on algorithms/physics
- significant improvements depending on algorithm

Compile-time merging of blocks

- forgo buffers if connection is known at compile-time
- enables compiler to "see" and optimise merged algorithm
- avoids loads & stores ⇒ less memory/cache required
- avoids synchronisation costs

benchmark:	cache misses	mean	stddev	max	ops/s
merged src→sink	1.3k / 3k = 46%	626 ns	110 ns	952 ns	16.4G
merged src->copy->sink	391 / 971 = 40%	957 ns	106 ns	1 us	10.7G
merged src(N=1024)->b1(N≤128)->b2(N=1024)->b3(N=32...128)->sink	398 / 960 = 41%	957 ns	103 ns	1 us	10.7G
merged src→mult(2.0)→divide(2.0)→add(-1)→sink	401 / 1k = 40%	3 us	108 ns	4 us	3.0G
merged src->(mult(2.0)->div(2.0)->add(-1))^10->sink	470 / 1k = 42%	41 us	189 ns	42 us	248M
runtime src->sink	9k / 174k = 5%	42 us	98 us	336 us	241M
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runtime src->mult(2.0)->div(2.0)->add(-1)->sink - process_one(..)	24k / 663k = 4%	105 us	259 us	882 us	97.5M
runtime src->mult(2.0)->div(2.0)->add(-1)->sink - process_bulk(..)	24k / 664k = 4%	152 us	358 us	1 ms	67.3M
runtime src→(mult(2.0)→div(2.0)→add(-1))^10→sink	56k / 686k = 8%	127 us	28 us	198 us	80.6M

CPU: AMD Ryzen 9 5900X (Zen 3)

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Big shout-out to: Dr. Matthias Kretz (GSI/FAIR) & C++ ISO Committee SG6 Numerics Chair for adopting us/GR and sponsoring the lib <simd> (↔ will be part of C++26)

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Modernisation Goals

improve performance, industrial integration+deployment

1. Preserve and Grow the existing diverse GR Ecosystem.
2. Clean- and Lean Code-Base Redesign
3. Performance Optimisations
4. **Tag-Based Timing System Integration**
   (White Rabbit, GPS, SW-based etc.)
5. Advanced Processing Features
6. Broaden Cross-Platform Support
7. User-pluggable Work Scheduler Architecture
8. Overall Project Direction

4. Tag-Based Timing System Integration

synch. data (streams) from different flow-graphs & nodes

- MIMO signals – if possible – are usually synchronised via each RX channel being on the same DAQ system
- not always possible: limited #channel per device (↔costs), largely spacially distributed DAQs (e.g. FAIR: 4.5 km)

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- real-world problem: (re-)synchronise physically/spacially distributed sources within the same flow-graph
  - failure cases to consider: ‘reconnecting/restarting SDRs/nodes’, ‘no data’ & time-outs, … clock-drifts, transmission delays, ...

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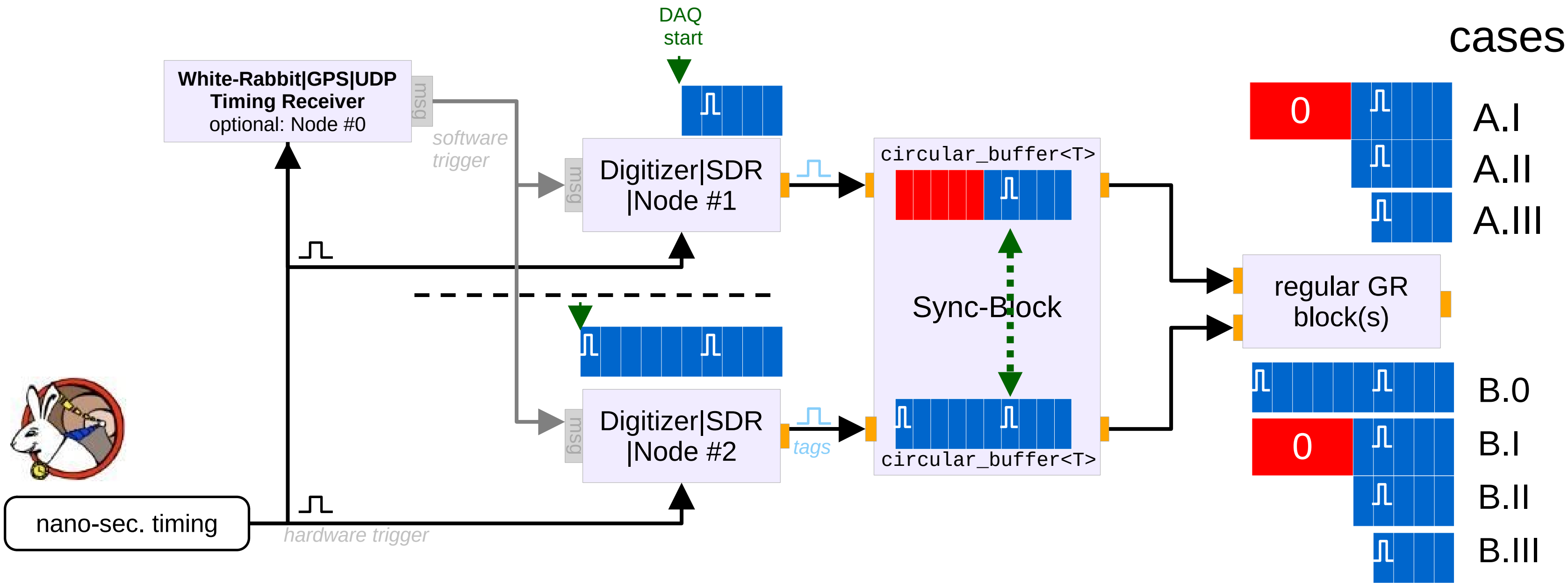

solved through standardised ‘`tag_t`’s;
TRIGGER_NAME, TRIGGER_TIME,TRIGGER_OFFSET

Modernisation Goals

improve performance, industrial integration+deployment

1. Preserve and Grow the existing diverse GR Ecosystem.
2. Clean- and Lean Code-Base Redesign
3. Performance Optimisations
4. Tag-Based Timing System Integration (White Rabbit, GPS, SW-based etc.)
5. **Advanced Processing Features**
   - transactional and multiplexed settings
   - synchronous chunked data processing
     (for event-based and transient-recording signals)
6. Broaden Cross-Platform Support
7. User-pluggable Work Scheduler Architecture
8. Overall Project Direction

5. Advanced Processing Features

Setting the scene – Issue with the existing Integration I/II

… open-hardware but not exclusive standard at FAIR: hundreds of other digitizers supported thanks to GNU Radio

Primary OpenDigitizer Applications:

A) First-line diagnostics
↔ "distributed ns-level synchronised oscilloscope/SDR/DSA/…"

B) Building blocks for higher-level diagnostics, monitoring, and feedback systems

C) Rapid Prototyping: accelerate integration of R&D prototype into robust 24h/7 operation

>500 DAQs & post-processing/monitoring feedback services
all sharing the same OpenCMW, GNU Radio, OpenDigitizer, and UI/UX software stack

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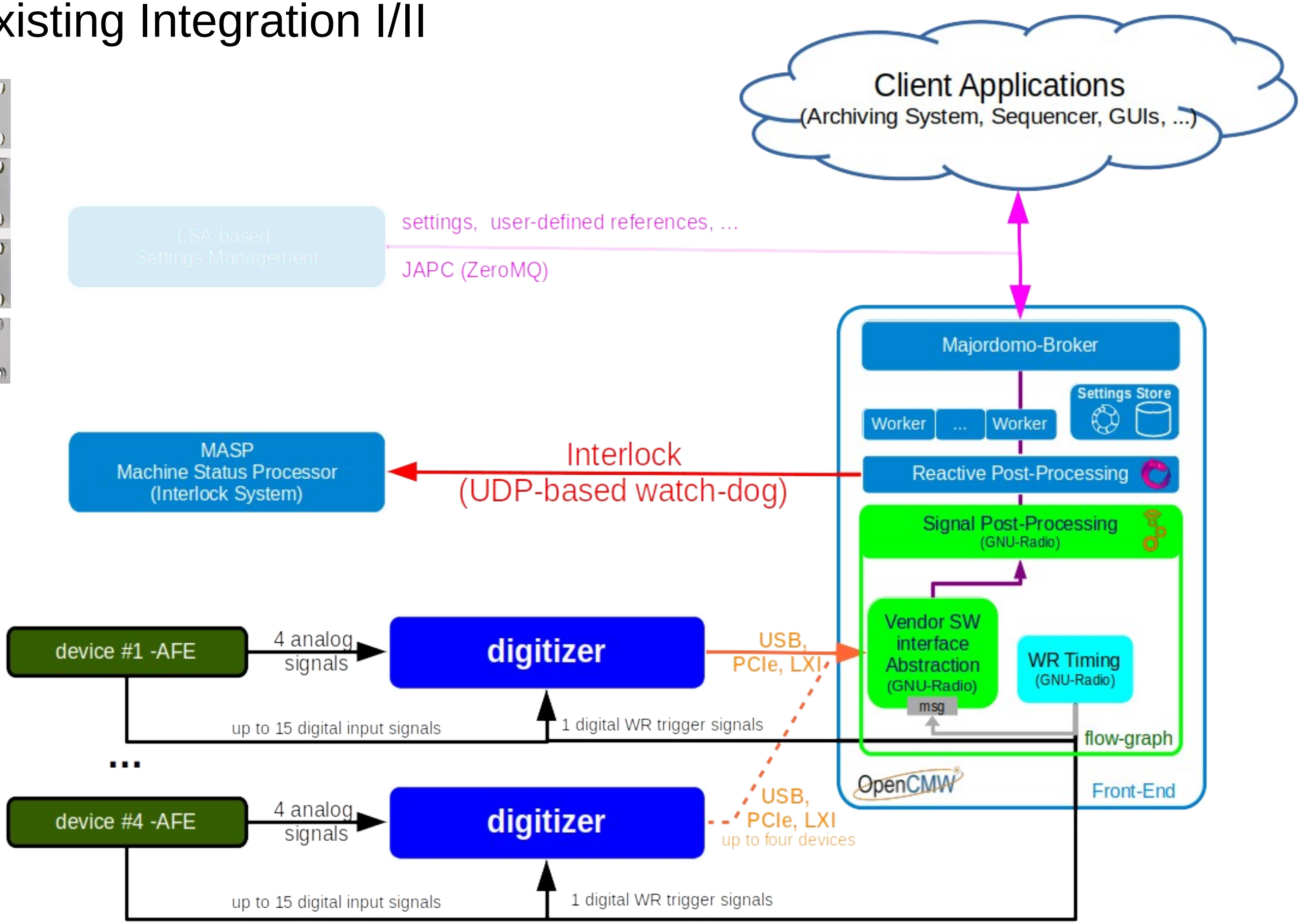

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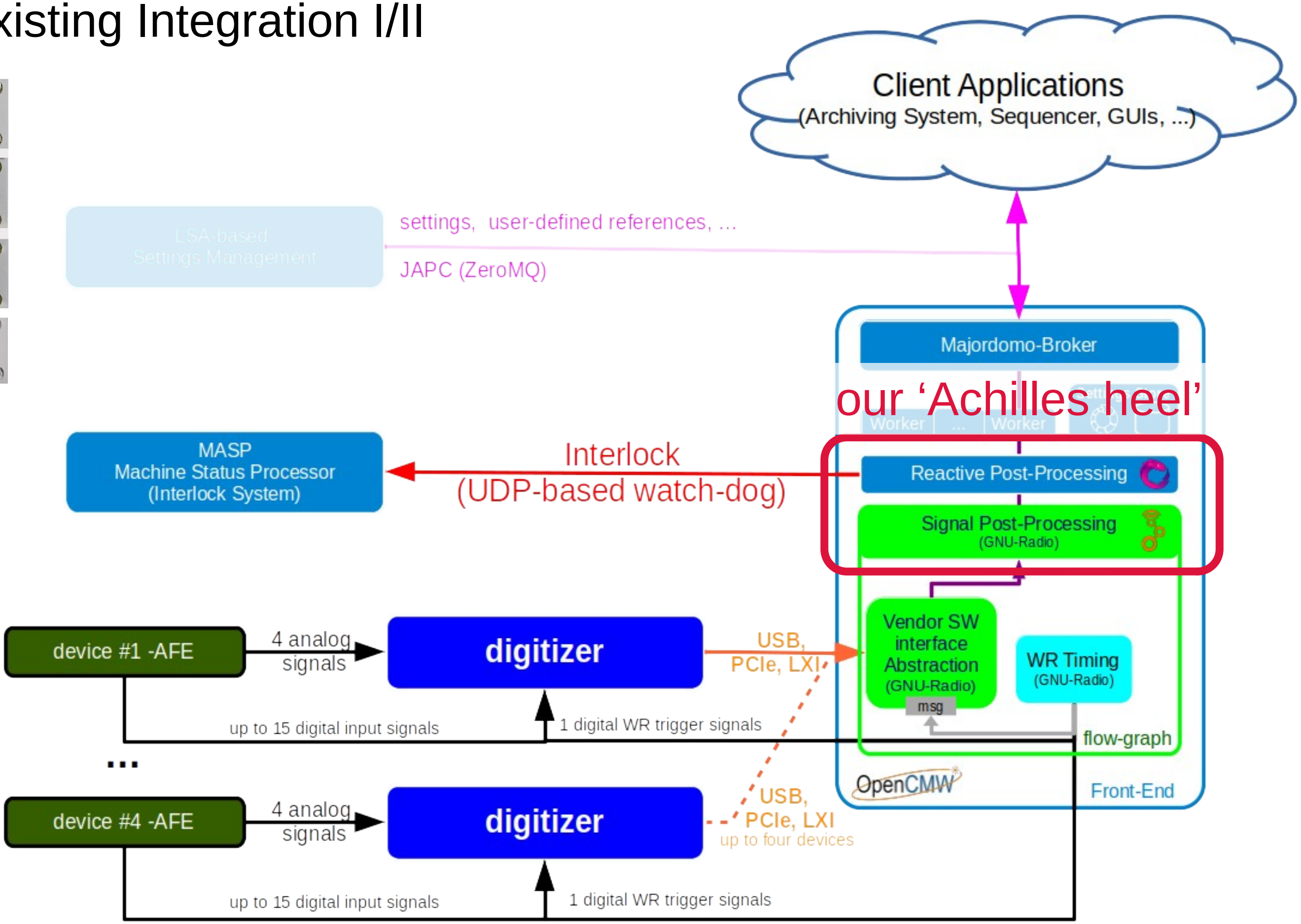

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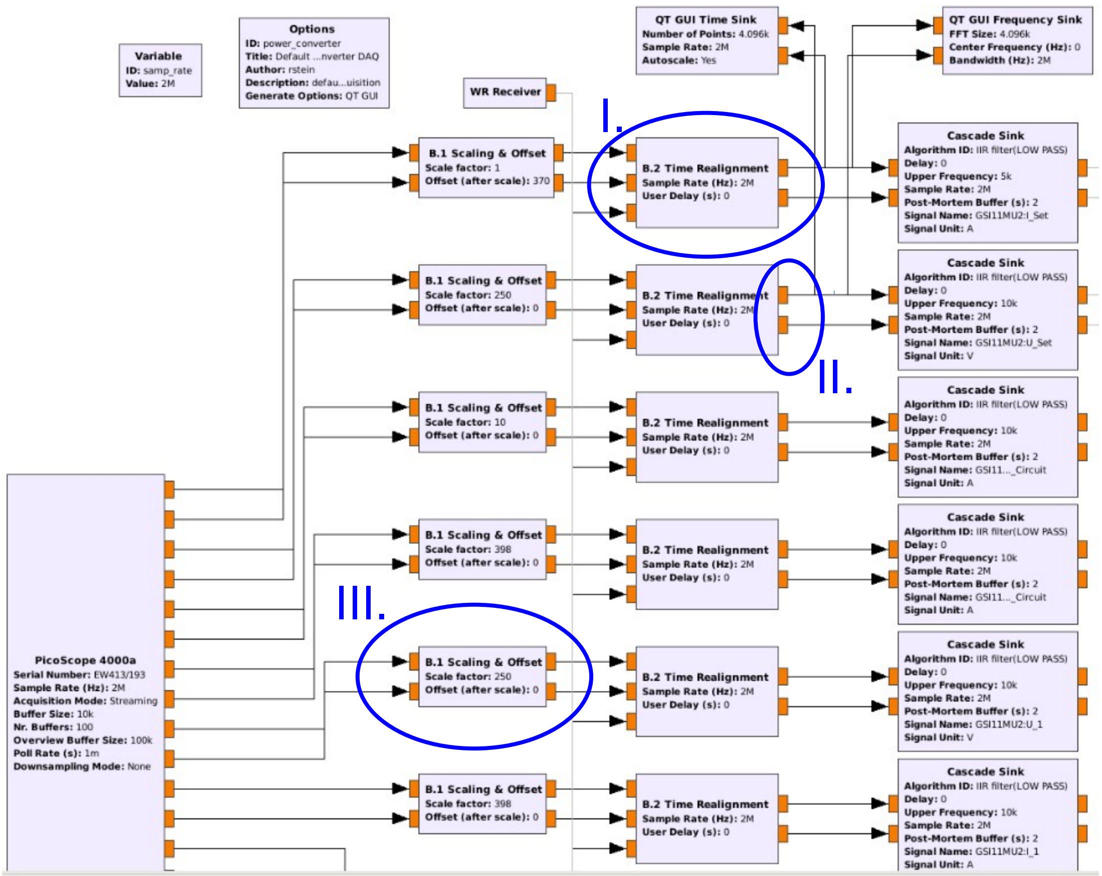


Three noteworthy things:

I. ns-level signal synchronisation across 300++ front-end controllers (FECs) via (https://github.com/fair-acc/gr-digitizers)

   a) ‘White-Rabbit’ timing receiver

   b) GPS pps signals

   c) SW-trigger (i.e. UDP multicast)

II. mean + stdev processing

   a) … scientific rigour

   b) … signal-integrity checks
      ↔ used in feed-back loops (automatic stop/fail-safe)

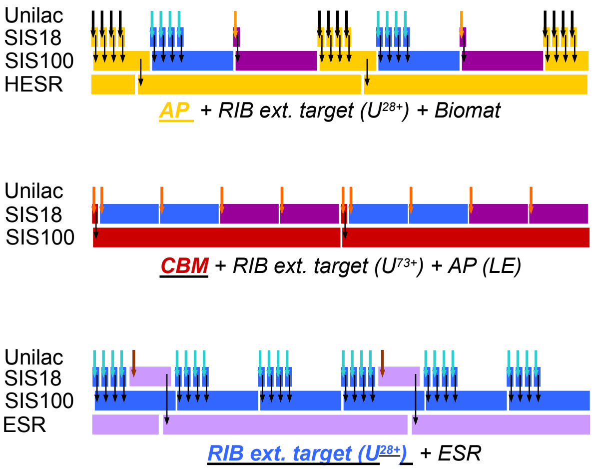
III. run-time flow-graph modifications (https://github.com/fair-acc/gr-flowgraph)

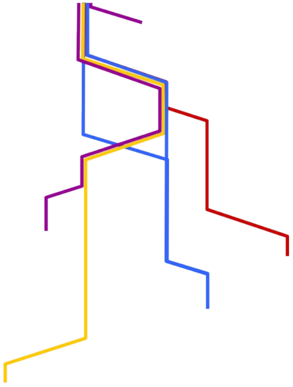
   a) block parameters
      (e.g. gains, timing-triggered threshold/interlock functions, χ^2-fits, conditional processing, …)

   b) online- & user-defined post-processing (~T&M equipment)

5. Advanced Processing Features

transactional and multiplexed settings – FAIR/CERN/… are multi-mission/user platforms





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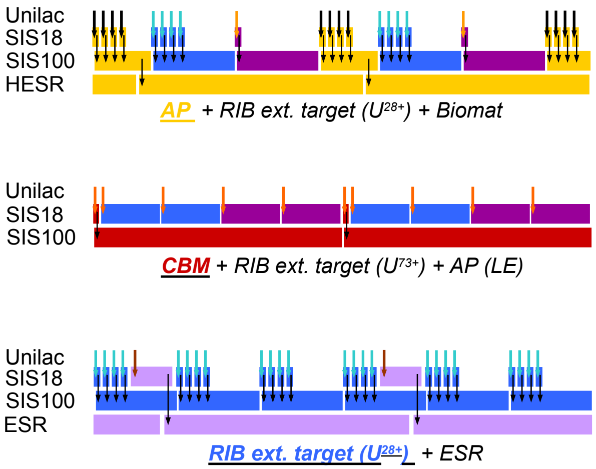

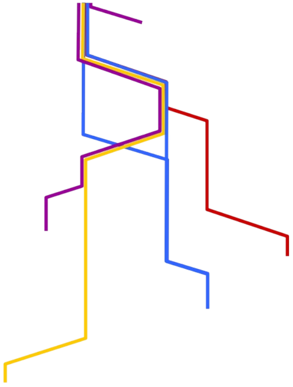

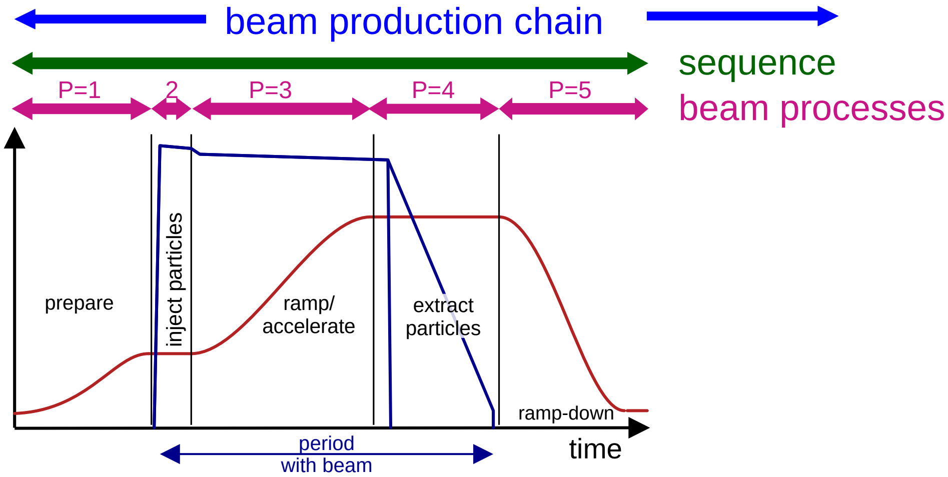

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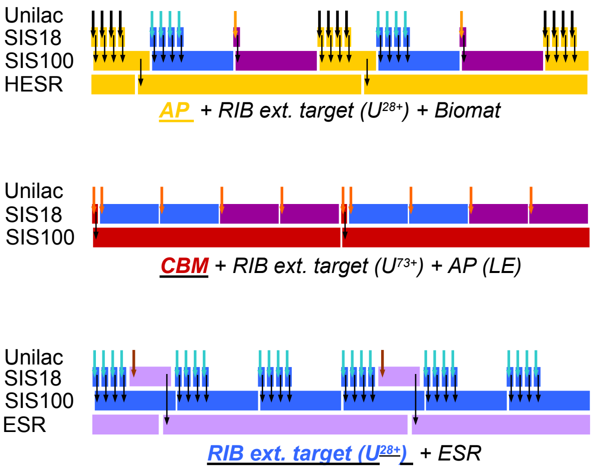
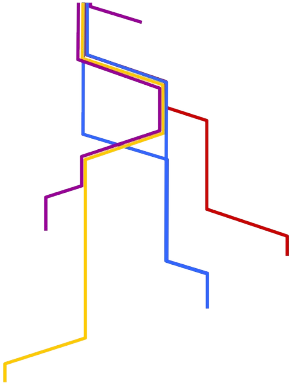
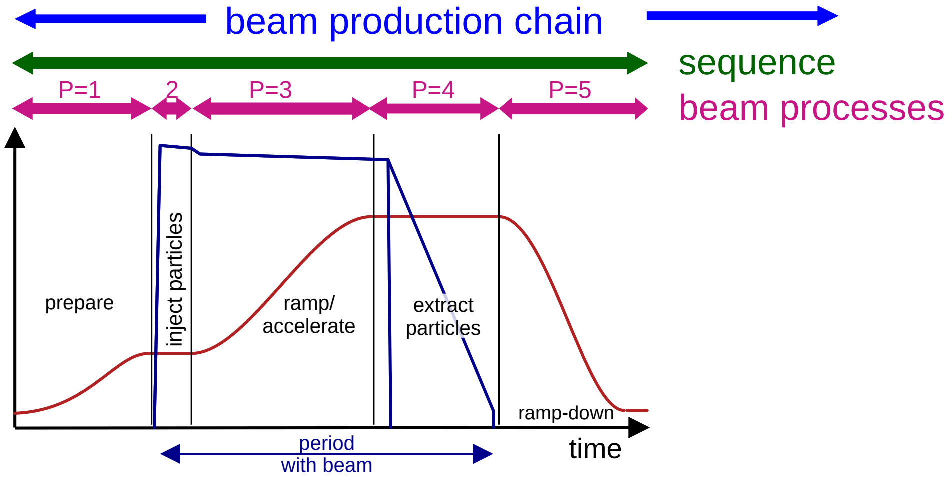
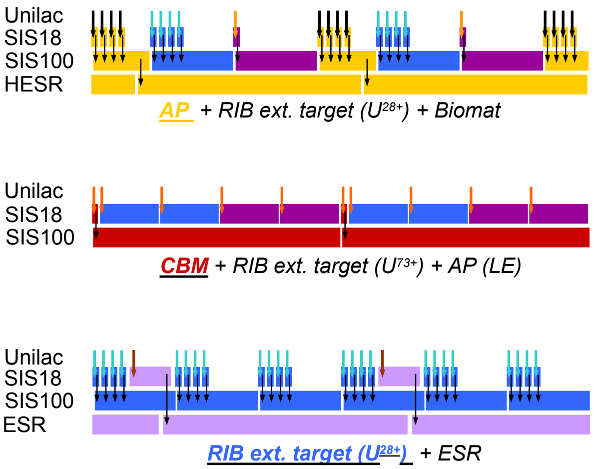


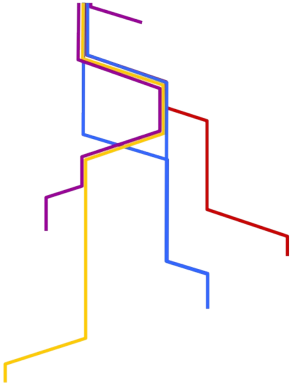


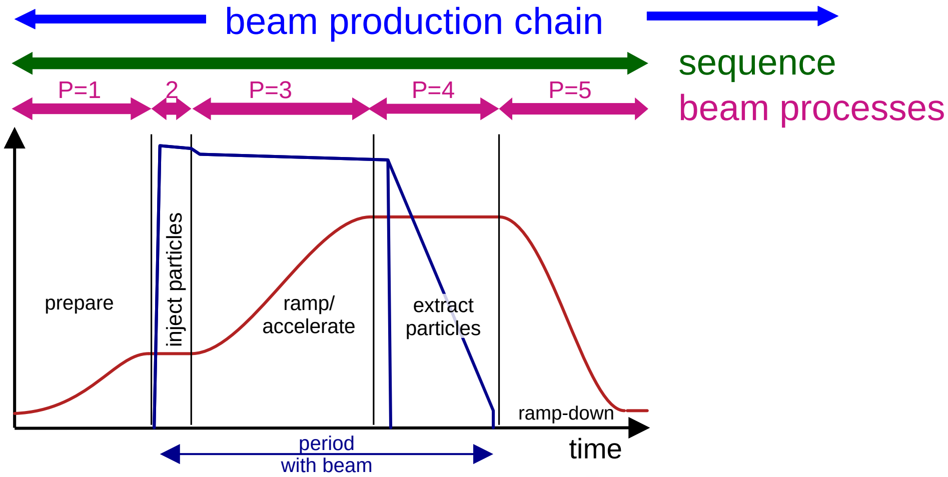


5. Advanced Processing Features

transactional and multiplexed settings – FAIR/CERN/… are multi-mission/user platforms







- Device/Block Settings Challenges:
  - frequent synchronised settings changes (10k+ devices!)
  - require dynamic coarse → fine-grained scope
  - data transport & signal processing group-delays

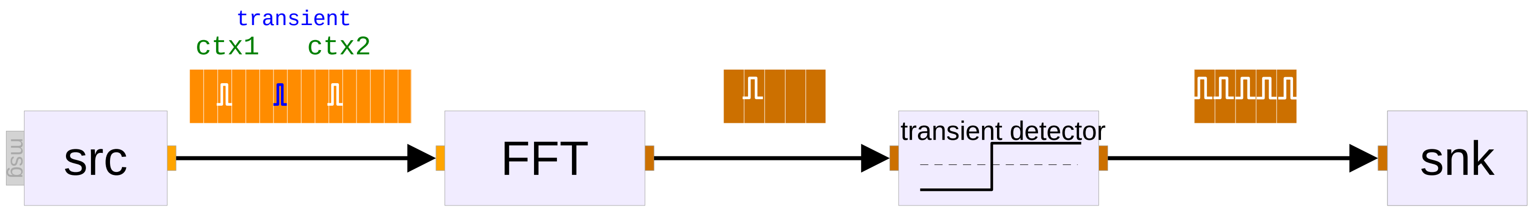
→ settings need to be synchronised & multiplexed

→ solution: adaptive timed B+-tree + transactions (see appendix)

FAIR GSI

5. Advanced Processing Features

synchronous chunked data processing → new DataSet<T>



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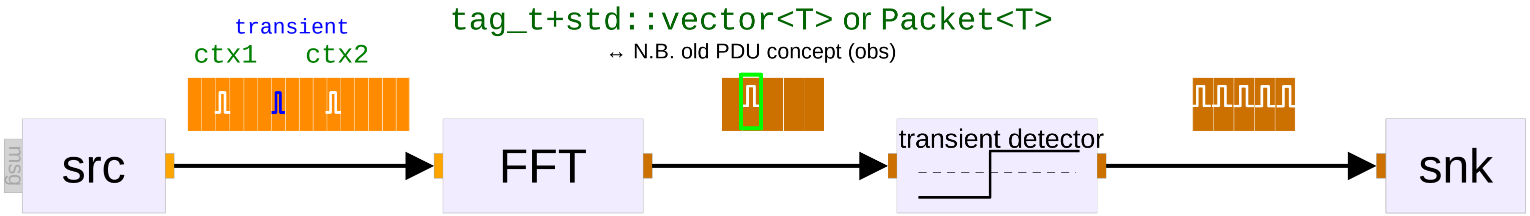

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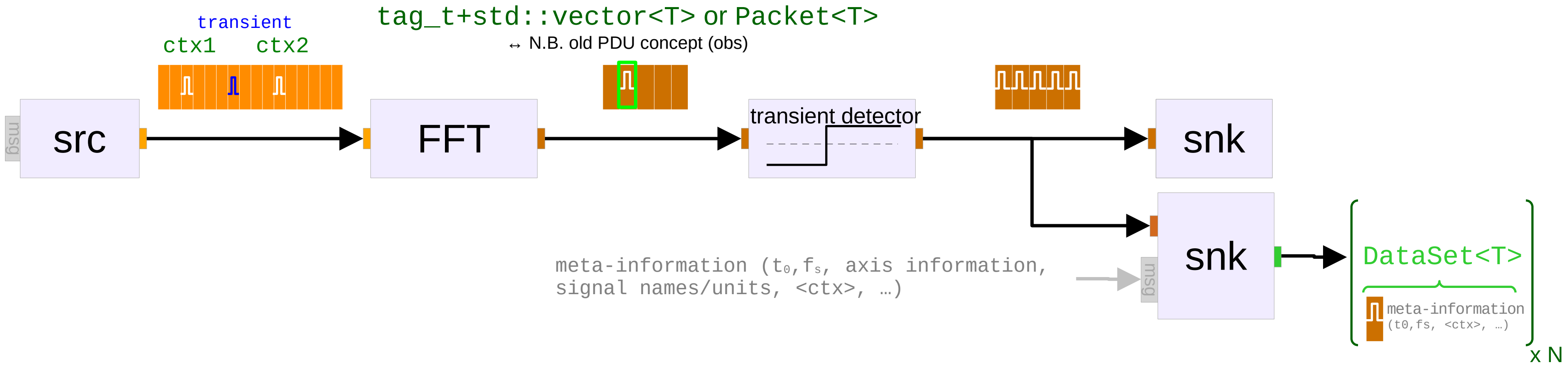

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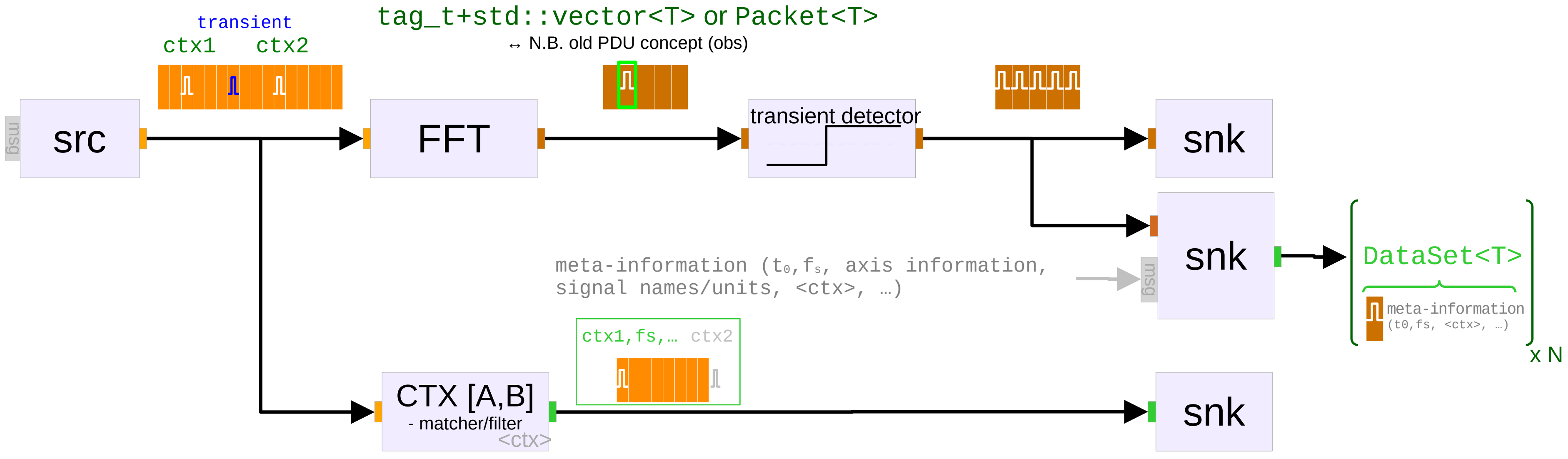

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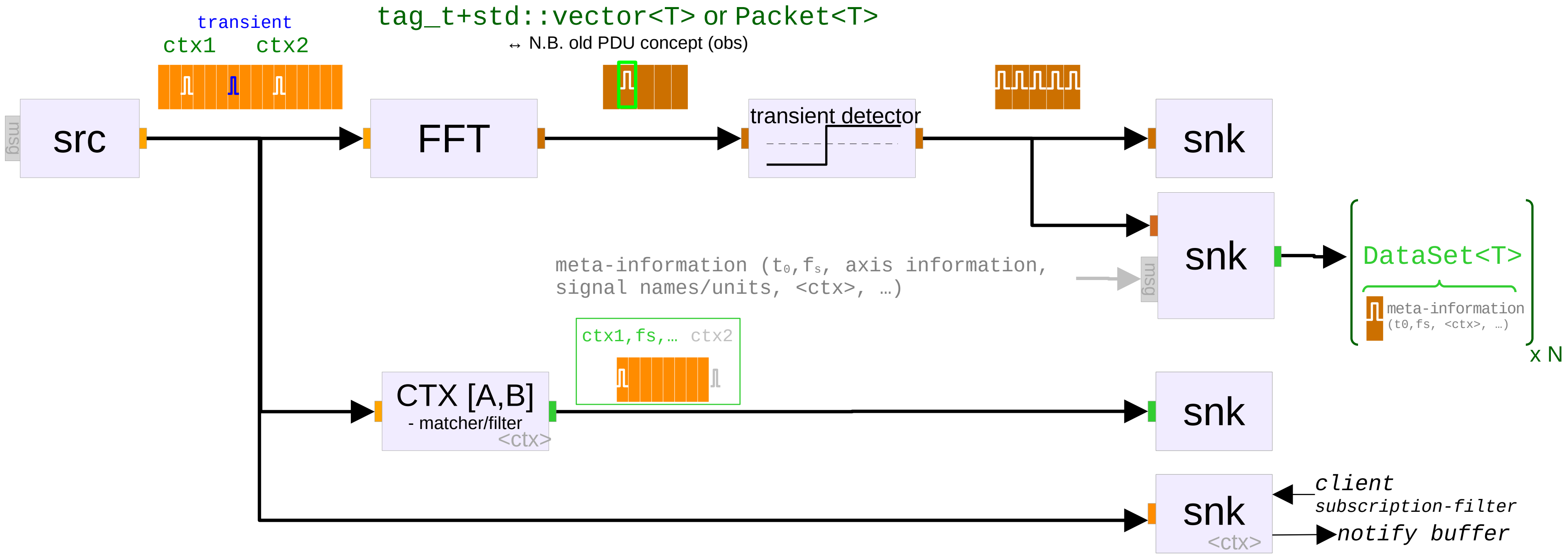

FAIR GSI

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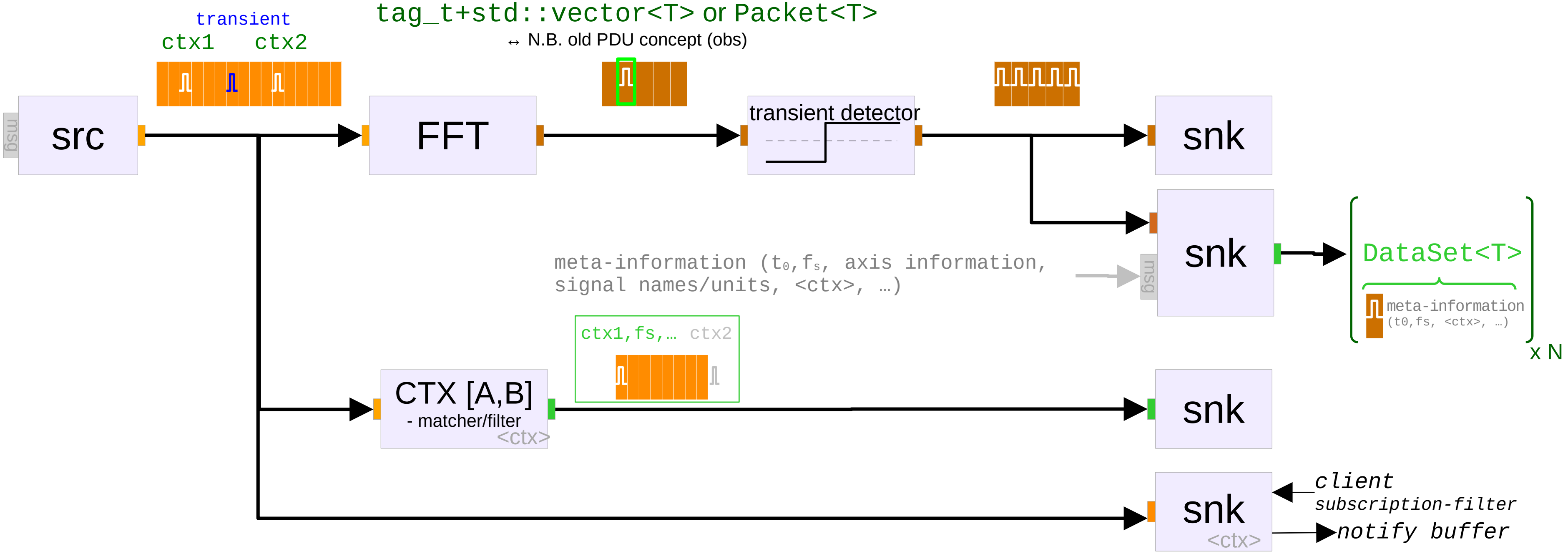
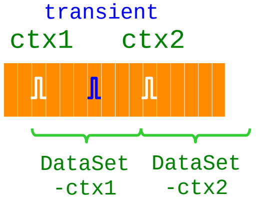


filter modes:

'multiplexed'



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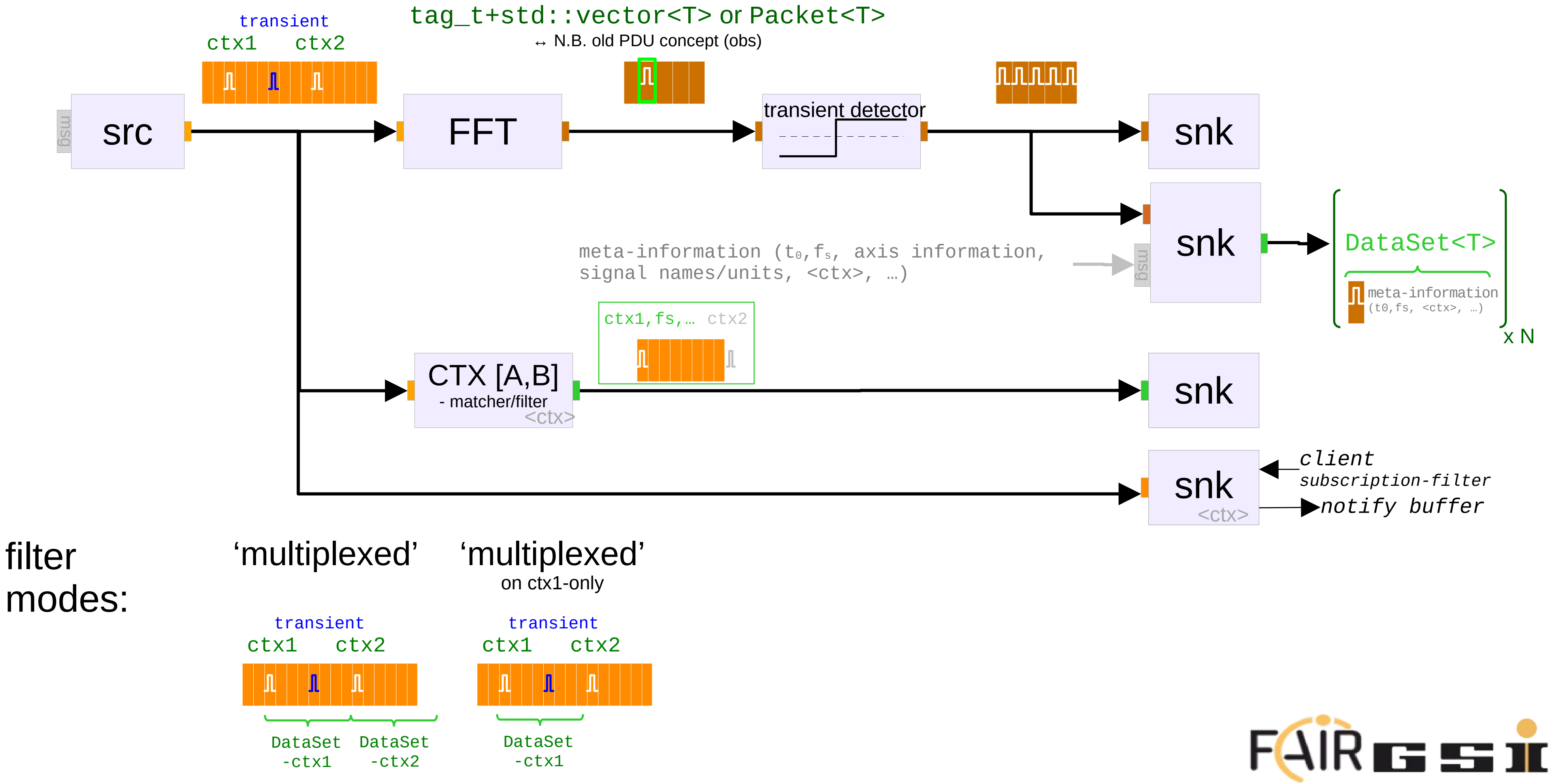

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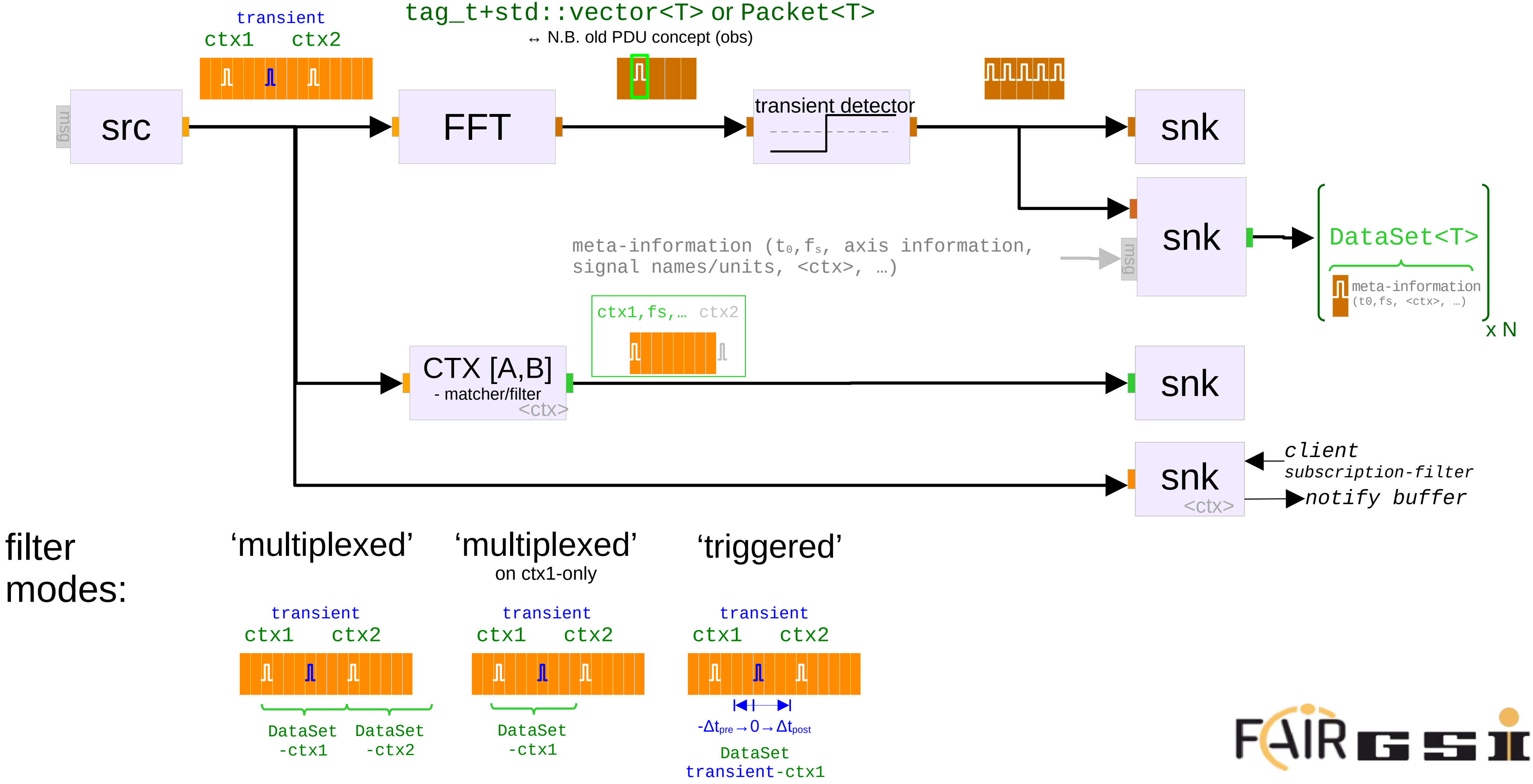

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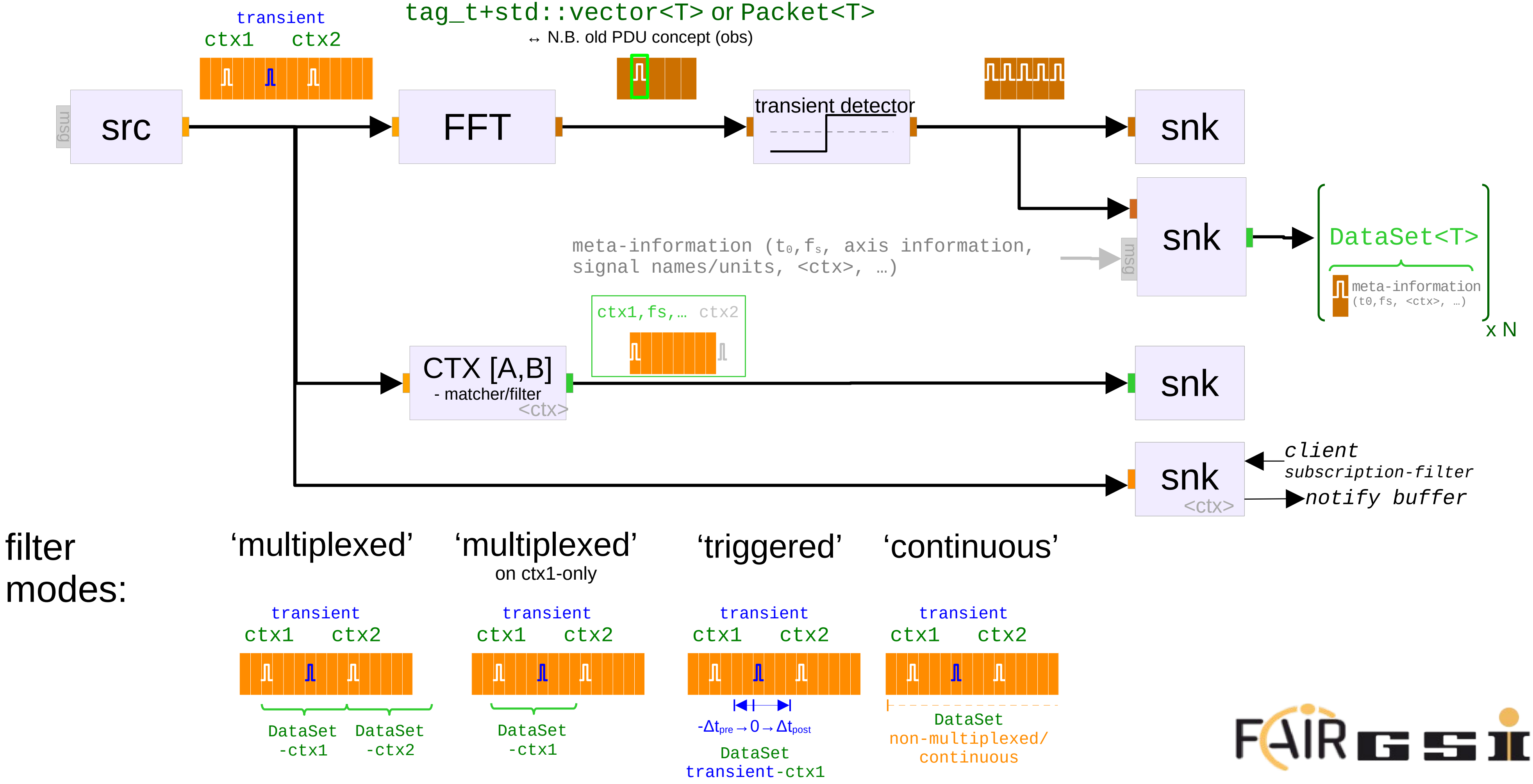

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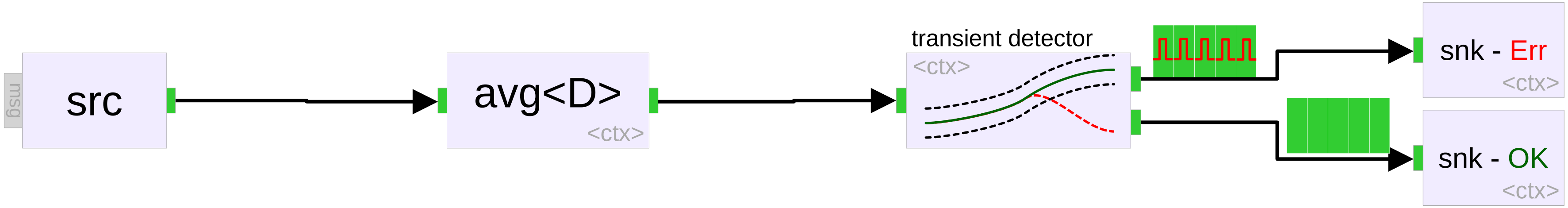

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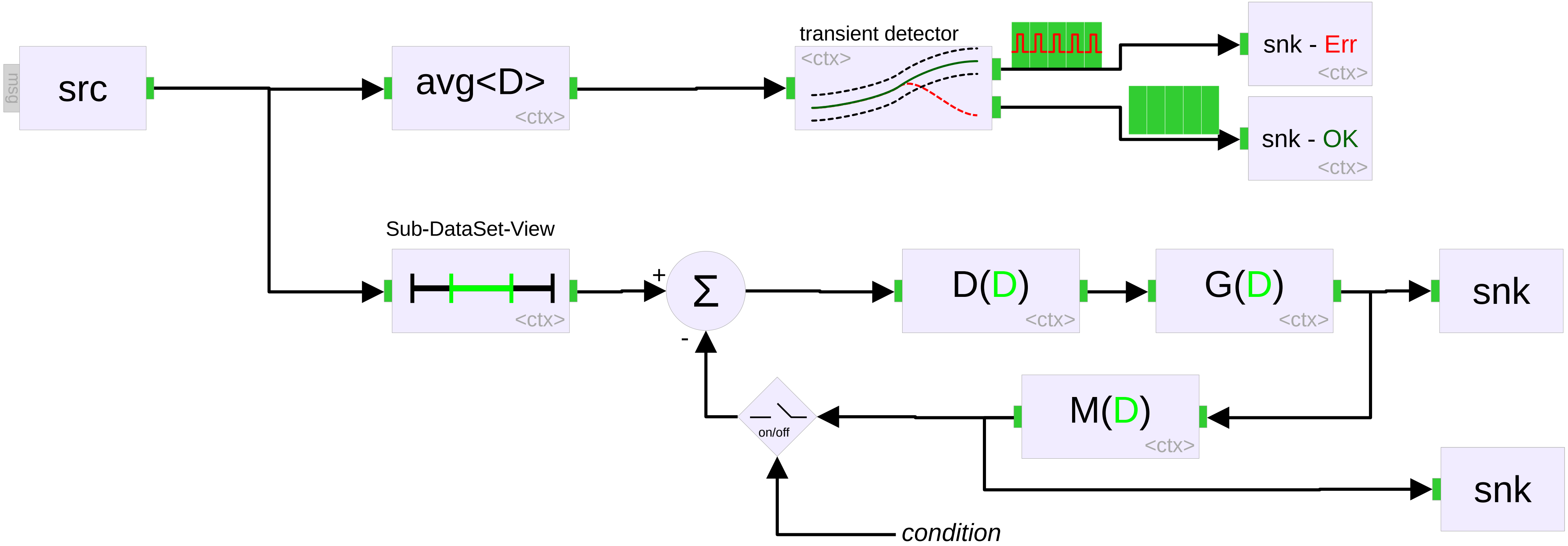

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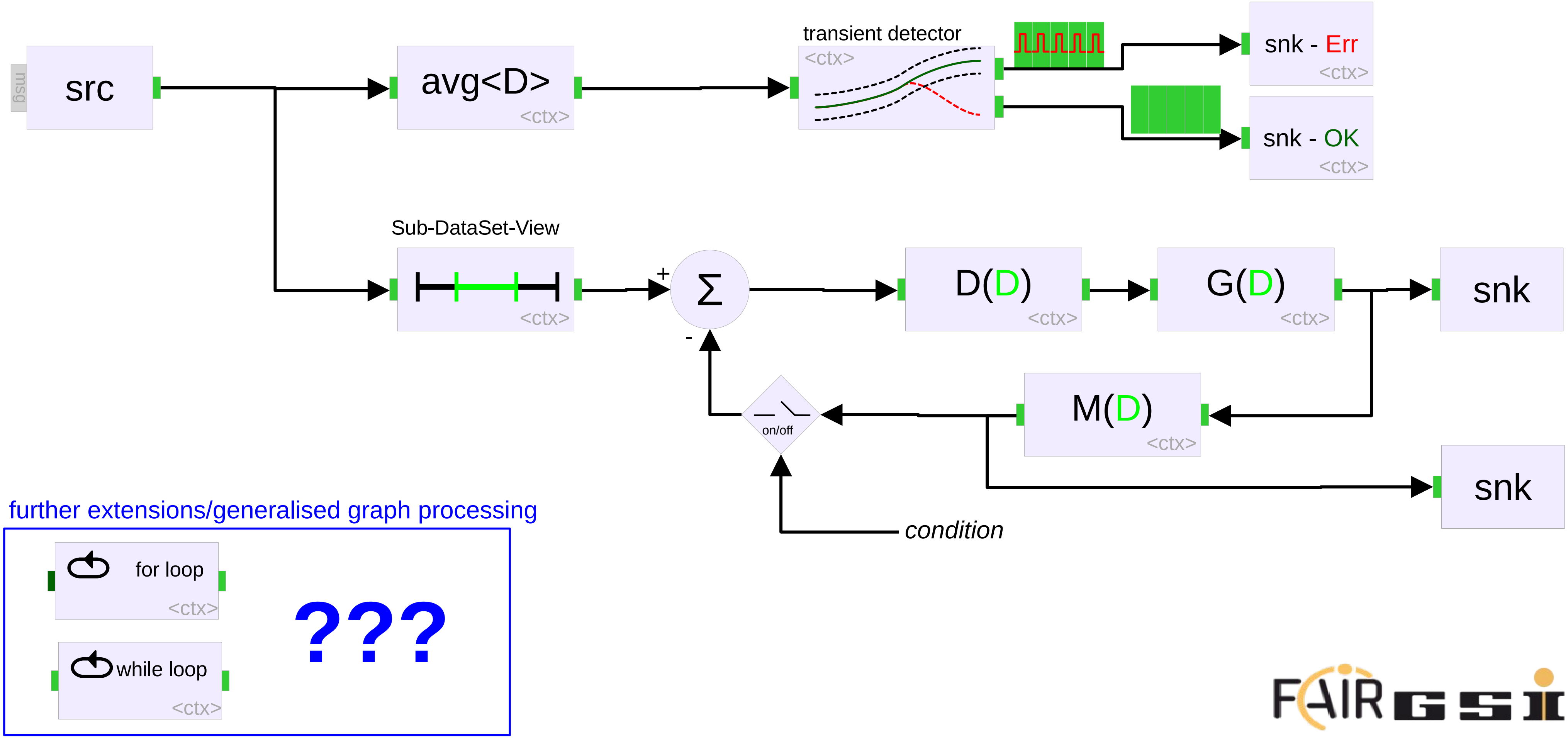


5. Advanced Processing Features

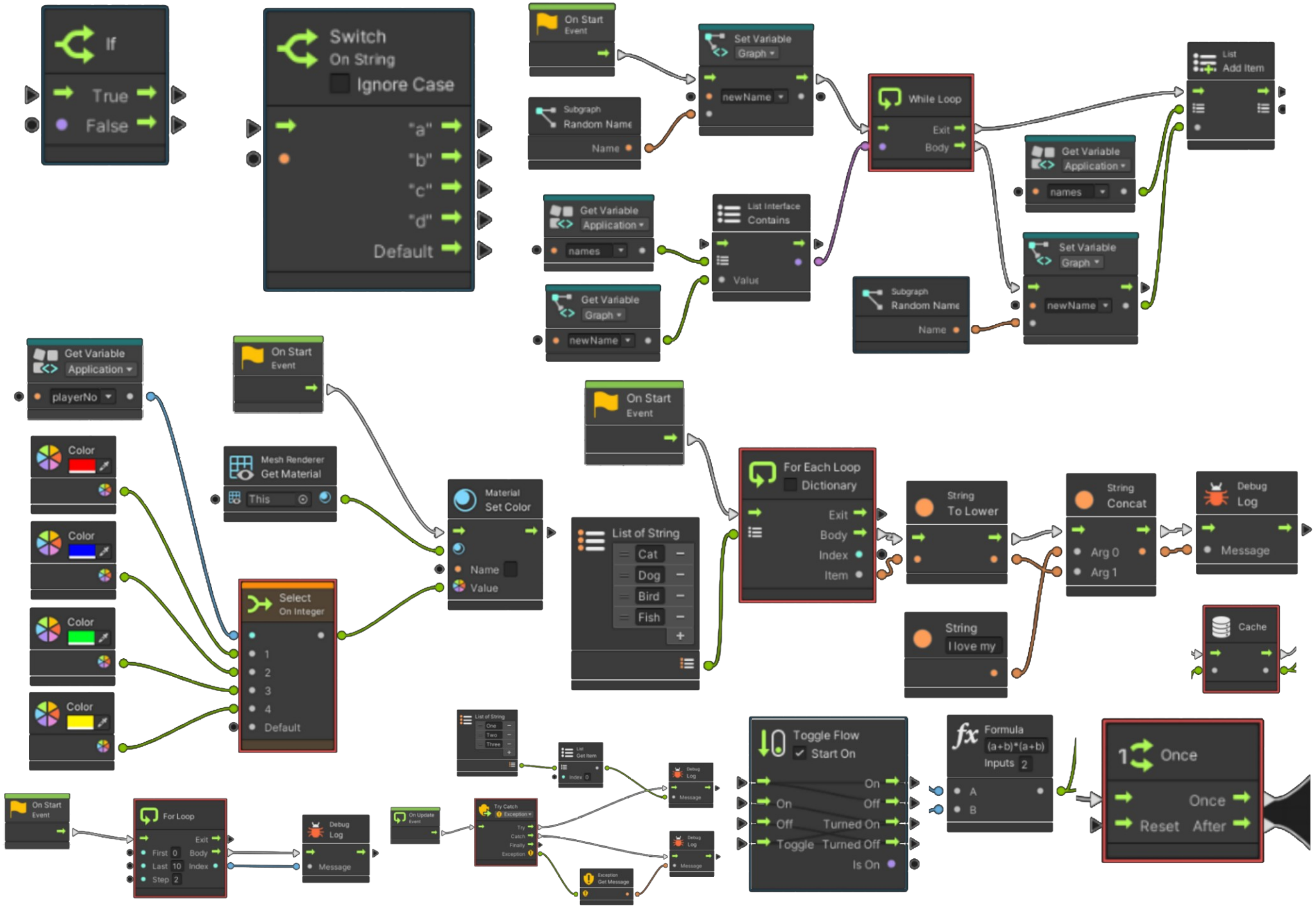
synchronous chunked data processing, three new types: `Packet<T>` → `Tensor<T>` → `DataSet<T>`

```
template<typename T>
struct DataSet {   // – numeric/measurement based data (e.g. generation of graphs/plotting)
 Packet
  Tensor
   std::int64_t                                  timestamp = 0; // UTC timestamp [ns]
   // axis layout:
   std::vector<std::string>                      axis_names; // e.g. time, frequency, …
   std::vector<std::string>                      axis_units; // axis base SI-unit
   std::vector<std::vector<T>>                   axis_values; // explicit axis values

   // signal data layout:
   std::vector<std::int32_t>                     extents; // extents[dim0_size, dim1_size, …]
   std::variant<layout_right, layout_left, std::string>  // row-major, column-major, “special”
                                                 layout;

   // signal data storage:
   std::vector<std::string>                      signal_names;  // size = extents[0]
   std::vector<std::string>                      signal_units;  // size = extents[0]
   std::vector<T>                                signal_values; // size = \PI_i extents[i]
   std::vector<T>                                signal_errors; // size = \PI_i extents[i]
   std::vector<std::vector<T>>                   signal_ranges; // [[min_0, max_0], [min_1, …]

   // meta data
   std::vector<std::map<std::string, pmt::pmtv>>  meta_information;
   std::vector<std::map<std::int64_t, pmt::pmtv>> timing_events; // ↔ gr::tag_t
   // [..] constructors, accessors, ...
};
```

Future Vision/Extension: Inspiration from Unity Control Node …

Basic Scripting of more complex signal flow/processing mechanisms

- https://docs.unity3d.com/Packages/com.unity.visualscripting@1.8/manual/vs-control.html



Modernisation Goals

improve performance, industrial integration+deployment

1. Preserve and Grow the existing diverse GR Ecosystem.
2. Clean- and Lean Code-Base Redesign
3. Performance Optimisations
4. Tag-Based Timing System Integration (White Rabbit, GPS, SW-based etc.)
5. Advanced Processing Features
6. **Broaden Cross-Platform Support** (including WebAssembly)
7. User-pluggable Work Scheduler Architecture
8. Overall project direction

6. Broaden Cross-Platform Support

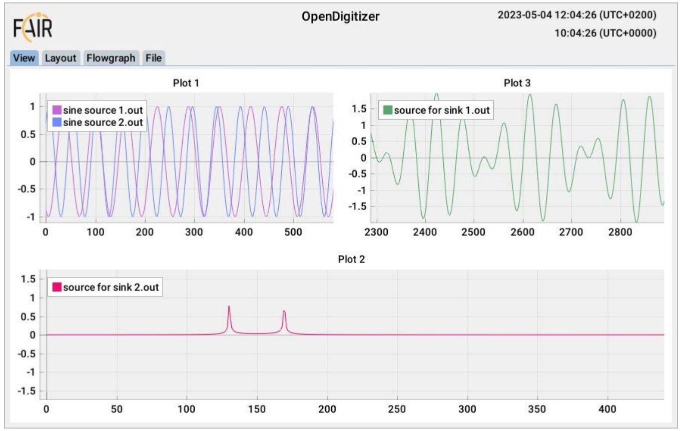
emphasis on GCC, Clang & Emscripten (↔ WASM/WebAssembly, UI) Support

Tech Demo:

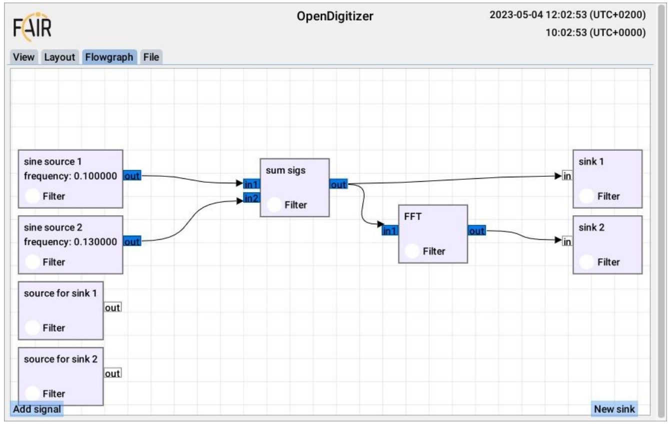
https://fair-acc.github.io/opendigitizer

- UI tooling is important for adoption, debugging and as a real world benchmark
  → core component of OpenDigitizer reimplementation.
- Simple to use basic functionality for day to day usage but no limitations for troubleshooting and expert users
  - direct access to the processing flowgraphs.
  - aim at full compatibility with GNU Radio Companions `'.grc'` file format
- Images show the current state of the working implementations and are subject to further development.

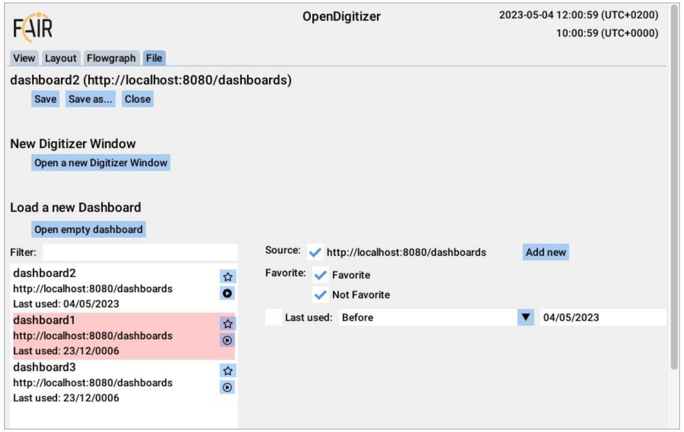
Default dashboard view (editable)



Display and modify service and post-processing flow graphs



Store and load custom dashboards



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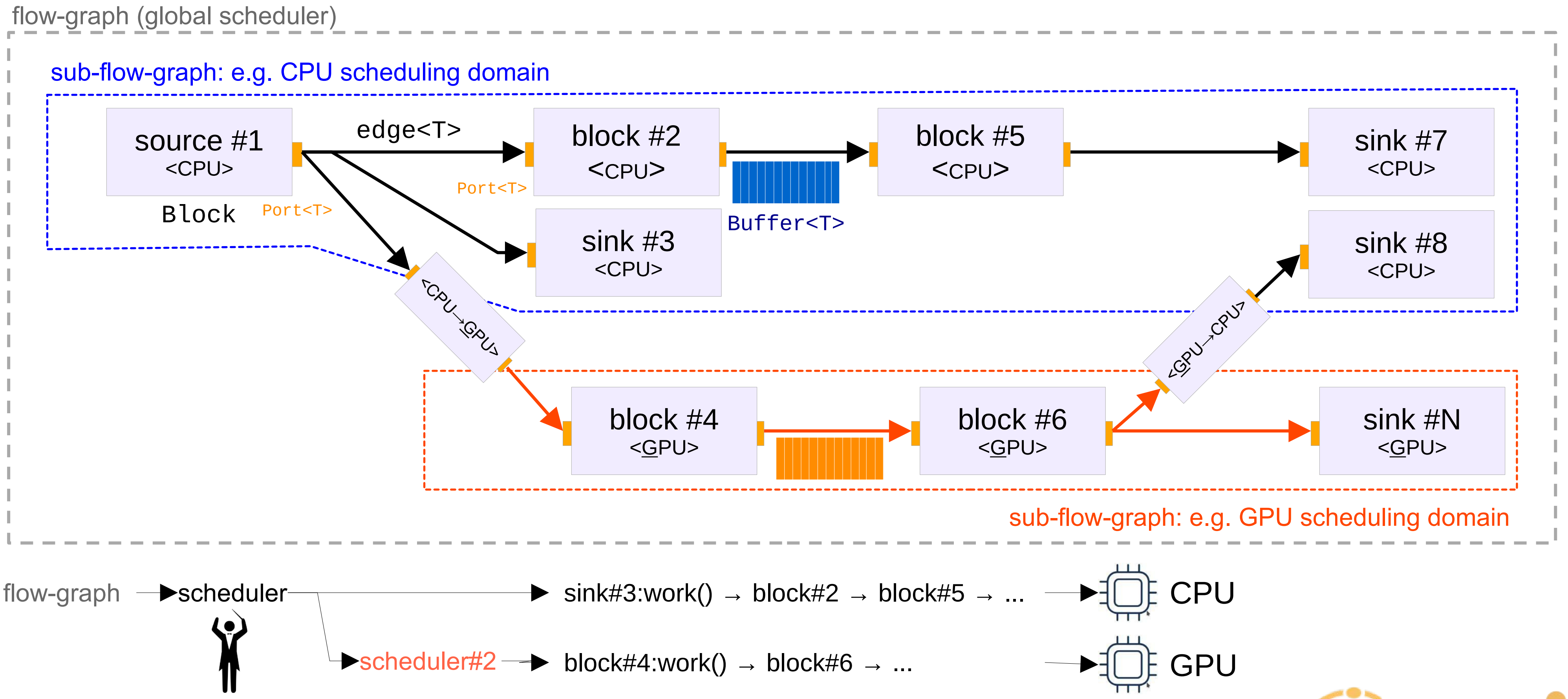
   - domain (e.g., CPU, GPU, NET, FPGA, DSP, …)
   - scheduling constraints – throughput vs. latency constraints
8. **Overall Project Direction**

7. User-pluggable Work Scheduler Architecture

Simplified Graph Topology adaptable to domain (e.g., CPU, GPU, NET, FPGA, DSP, …)



7. User-pluggable Work Scheduler Architecture

Original Scheduler definition: https://gist.github.com/mormj/9d0b14d6db59ee7f313755c76498cc91

- The scheduler interface is responsible for execution of part (or all) of a flowgraph. Schedulers are assumed to have an input queue and the only public interface is for other entities (either from the runtime or other schedulers) push a message into the queue that can represent some action.

- These messages can be:
  - Indication that streaming data has been produced on a connected port
  - An asynchronous PMT message (indication to run callback)
  - Other runtime control (start, stop, kill)

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to note:

- description is effectively of an ‘orchestrator’ within a ‘microservice architecture’ (alt) using a message passing system to synchronising individual service task.

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to note:

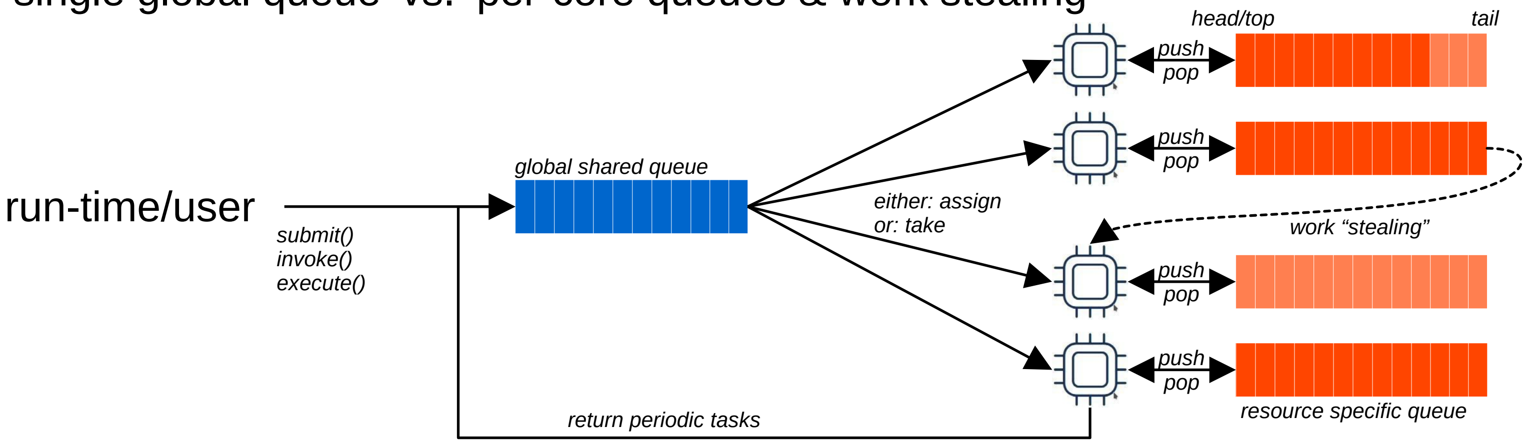
- description is effectively of an ‘orchestrator’ within a ‘microservice architecture’ (alt) using a message passing system to synchronising individual service task.
- message-passing has it’s costs and is not the most effective pattern for signal-processing

→ invert the dependency hierarchy and adopt existing scheduler designs to the problem

7. User-pluggable Work Scheduler Architecture

Modified Work Scheduler Paradigm/Proposal building upon that … I/II

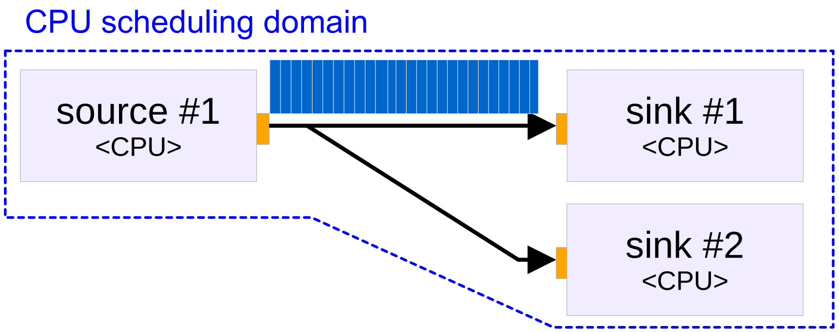
- a `scheduler`' is a process that assigns a task i.e. `` `block::work()' `` function to be executed an available computing resources (CPU|GPU|...).
  - A) `` `work()' `` encapsulates impl. specific `` `work(wio') `` function (`wio` ↔ ports, connection, buffers, …)
  - B) only non-blocking work functions, and
  - C) only as many threads as there are available computing resources
    - one core can execute only one thread at a time
    - avoids unfair/non-deterministic scheduling, context-switching & keeps L1/L2/L3 caches hot ↔ CPU shielding/affinity
- high-level scheduler implementation specific design choices:
  ‘single global queue’ vs. ‘per-core queues & work stealing`



7. User-pluggable Work Scheduler Architecture

Modified Work Scheduler Paradigm/Proposal building upon that … II/II

- need to be mindful that we need multiple distinct scheduler for, e.g.
  - CPU: default, fair, real-time, O(1), … (e.g. prefer small data chunks ↔ L1/L2/L3 cache & SIMD performance)



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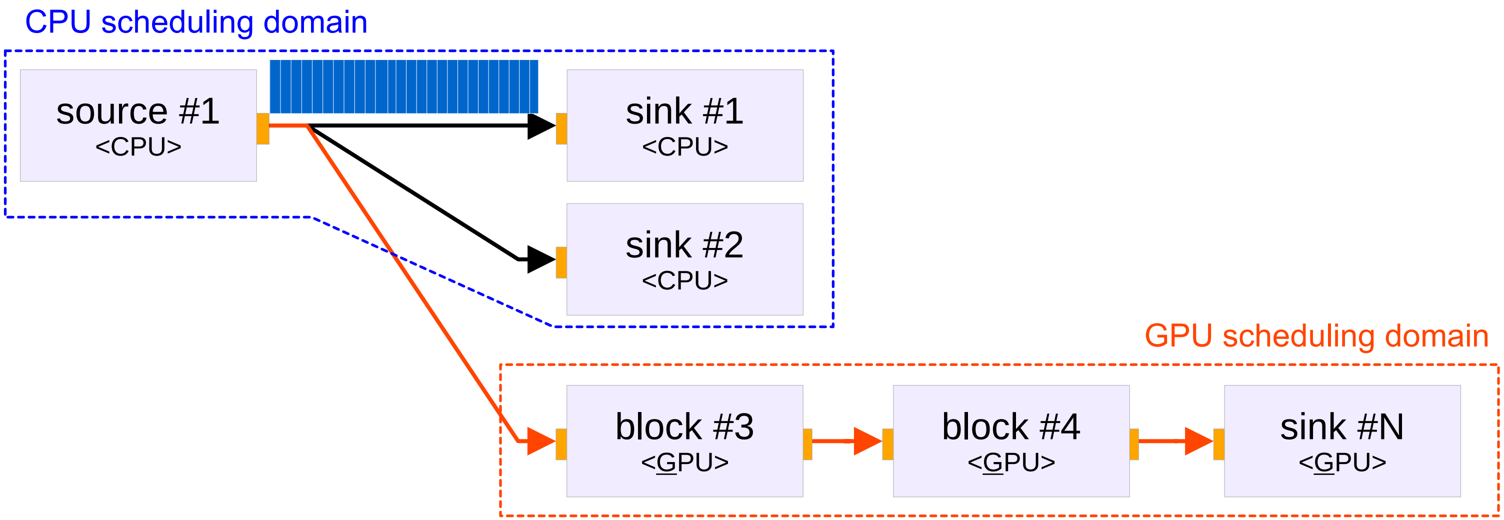
  - GPU: … (e.g. large chunks crossing CPU-GPU boundary, small for parallelising in-GPU processing ↔ >500 cores)
- scheduling decision needs to be done by scheduling thread (N.B. 'by block worker' only as fall-back)



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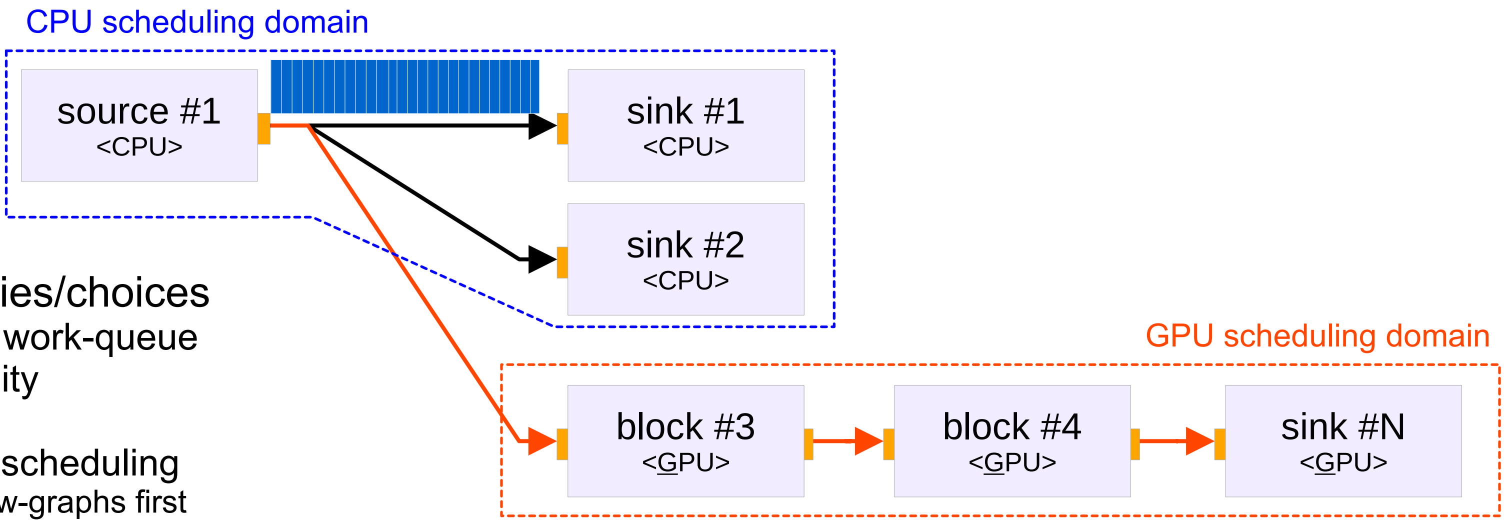
- scheduling decision needs to be done by scheduling thread (N.B. 'by block worker' only as fall-back)
- different scheduling strategies use different prioritisation & graph-based queues

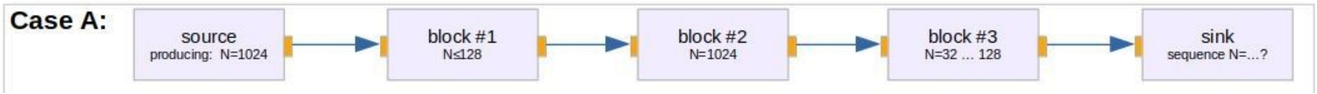


some scheduling strategies/choices

- global vs. per-thread/core work-queue
- CPU shielding/thread affinity
- static scheduling
- round-robin vs. prioritised scheduling
  - dependent/pre-requisite flow-graphs first
  - real-time vs. non-real-time sub-flow-graphs
  - data chunk-size based

7. User-pluggable Work Scheduler Architecture

Some Topologies specific designed to trip-up schedulers 😈 😇



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exercise:
what is the correct, best, and most efficient execution order?

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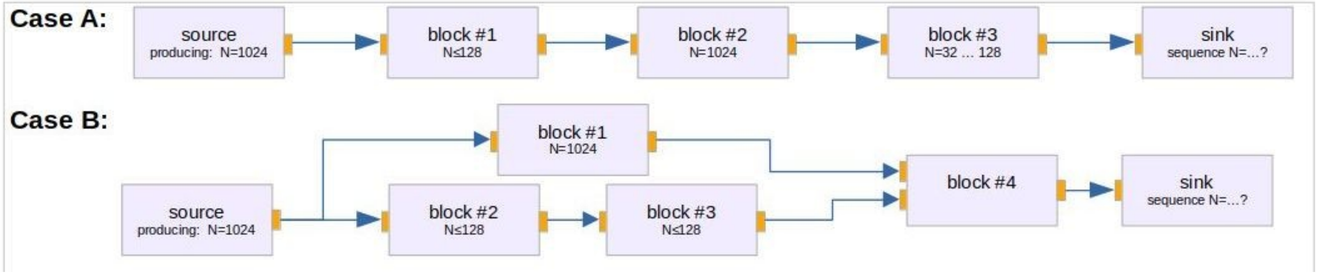

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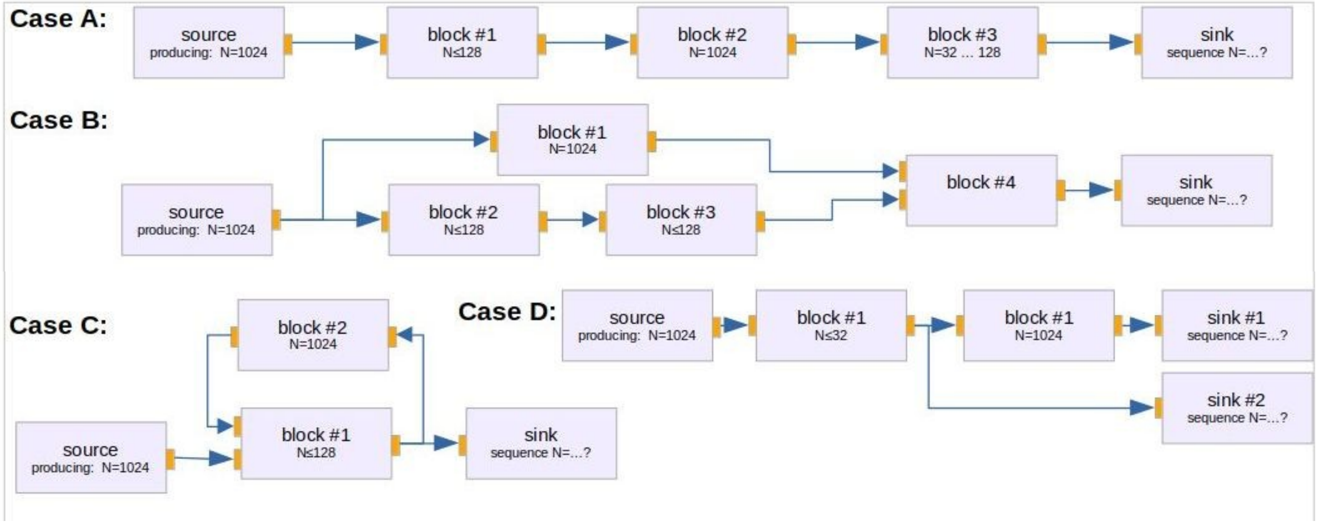

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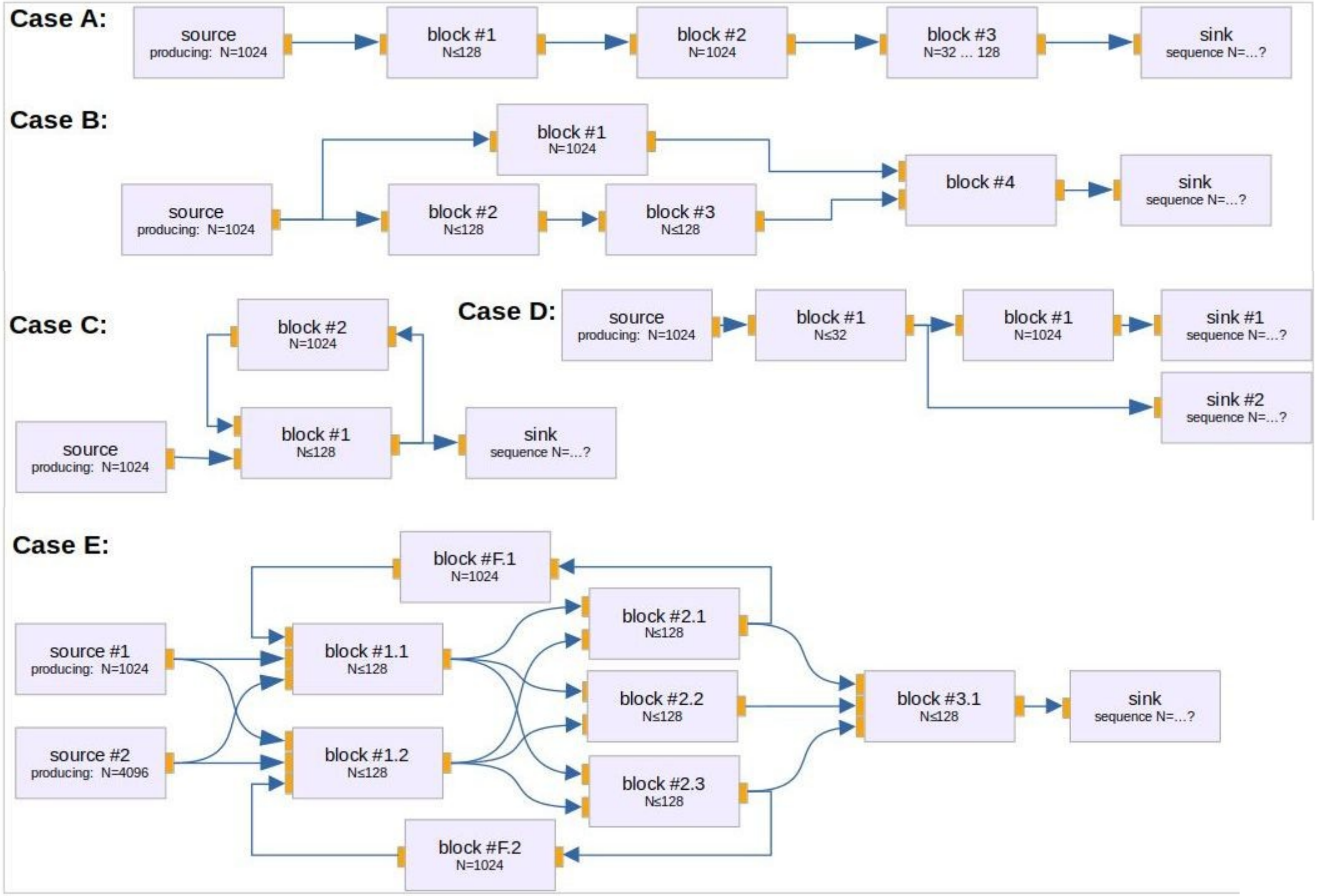

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FAIR GSI

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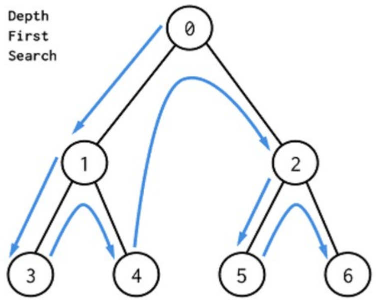
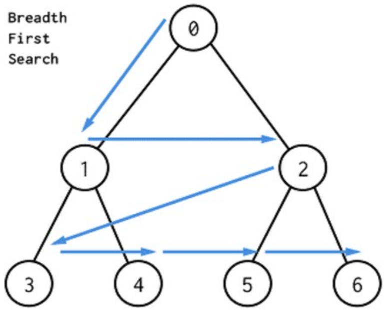
Implemented initially only the most basic scheduler strategies to test and verify API

0. Busy-Looping → naive implementation
1. Depth-first



2. Breadth first



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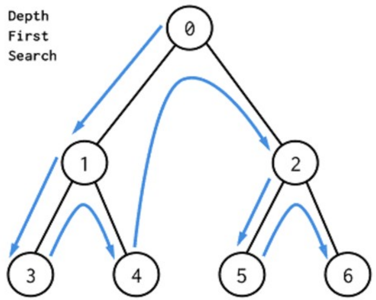

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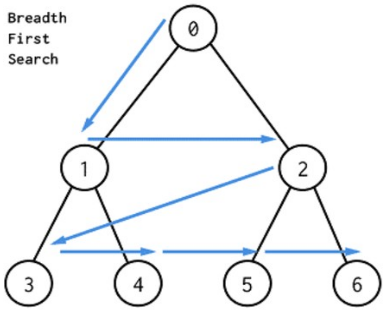

Other possible Algorithms:
https://github.com/fair-acc/graph-prototype/blob/main/include/README.md

- Topological Sort
- Critical Path Method (CPM) → minimizes total completion time
- A* → shortest path
- Wu Algorithm → minimal execution time
- Johnson's Algorithm → CPM on multiple processor cores
- Program Evaluation and Review Technique (PERT)
- Belman-Ford Algorithm
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- … combinations of the above and many more

Next Step: GNU Radio competition to find the best 'default', 'real-time', 'throughput' optimising scheduler for the outlined benchmark topologies.

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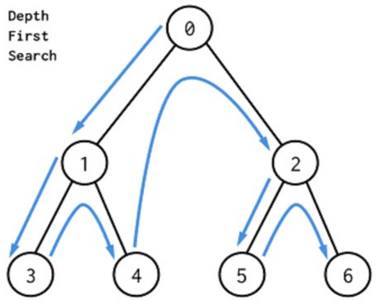

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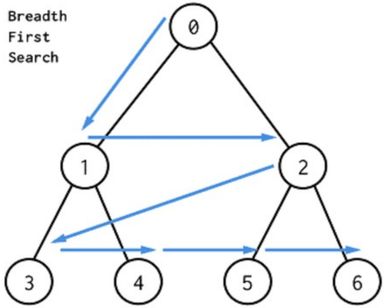

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Big shout-out to: Alexander Krimm for fleshing out the first PoC schedulers (pls. buy him a beer)

FAIR GSI

Modernisation Goals

improve performance, industrial integration+deployment

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8. **Overall Project Direction**

9. Overall Project Direction

Main Theme: Powerful CPU Core

- Addressing HPC limitations identified in dev-4.0
- Building upon Josh’s et al. foundation (see his intro)
- Optimising performance and scalability
  → Scheduler User Challenge

- **Usability Enhancements:**
  Classic GNU Radio Look & Accessibility

- Integrating trusted design features of traditional GR
- Simplifying & improving user interface for efficiency
- Expanding accessibility and user-friendly features

Steps for graph-prototype → GR 4.0
https://github.com/fair-acc/graph-prototype

1. C++ GR Framework: establishing a robust and flexible core foundation, follow-us on:
   https://github.com/orgs/fair-acc/projects/5/views/1
   https://github.com/fair-acc/opendigitizer/issues/46

2. GRC Integration: aligning functionalities for a cohesive user interface.

3. Python Integration: Harnessing the capabilities of Python for extended functionality.

9. Overall Project Direction

The next Frontier – FPGA Integration

Need:

- Ensuring agile real-time signal processing capabilities
- Efficiently integrating with low-level RF feedback systems

Challenge:

- Transitioning from semi-static firmware configurations
- Overcoming dependencies on proprietary tool-chains
- Simplifying the deployment process for diverse users

Vision:

- Advancing FPGA capabilities for dynamic adaptability
- Supporting real-time reconfiguration w/o disruptions
- Unified platform for both SW- and HW-processing

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Thank You!

looking forward to:

GNURadio 4.0

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

Looking forward to technical dialogue
and building partnerships … Questions?

Appendix

Modernisation Goals

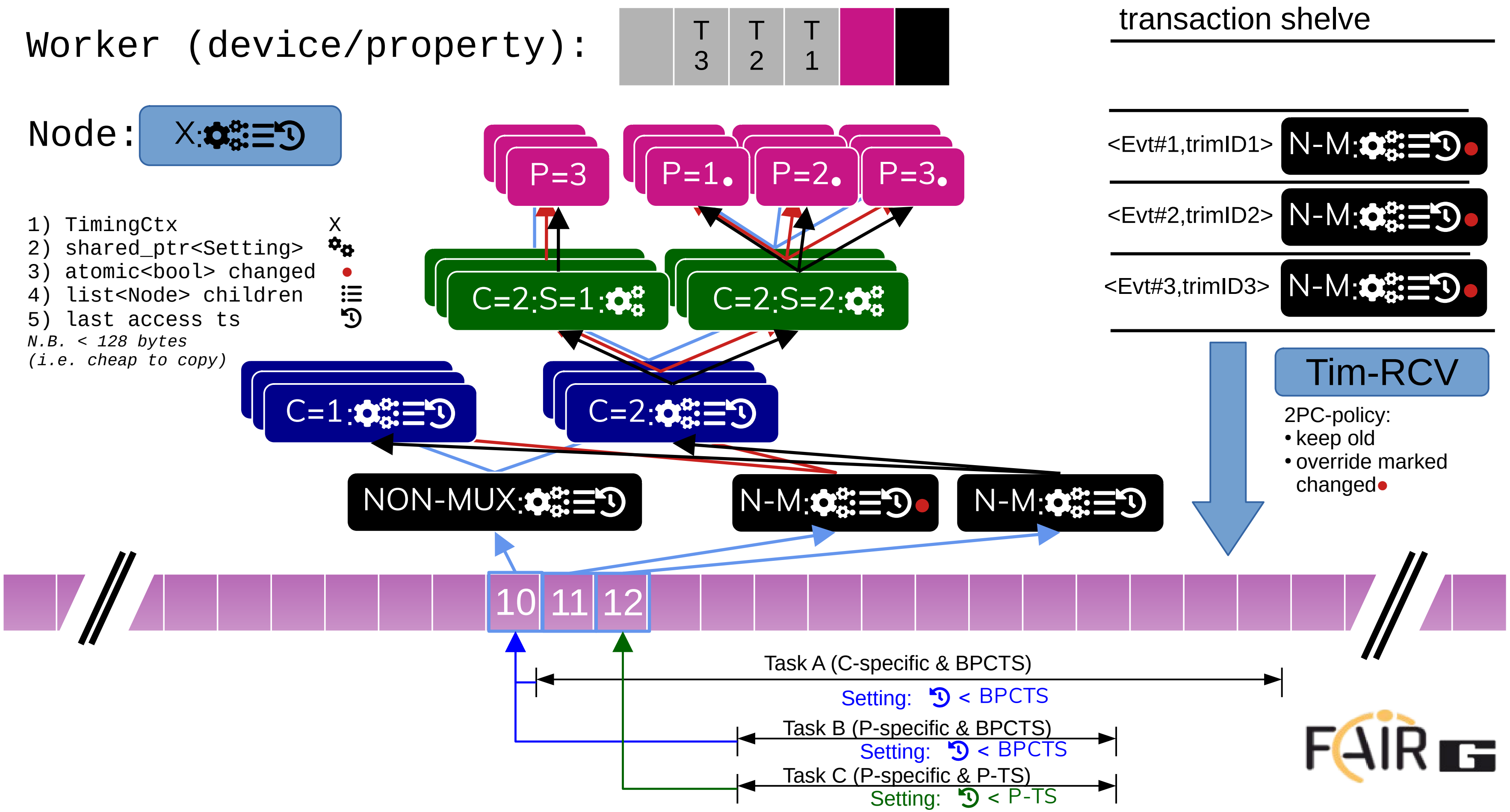
improve performance, industrial integration+deployment

1. **Preserve and Grow the existing diverse GR Ecosystem.**
   - thin Python interface over C++ API
   - avoid Python-only implementations (except OOT modules)
   - swappable runtime components (both in and out of tree)
   - simplified block development: get block developers to "insert code here" without lots of boilerplate or complicated code
2. **Clean- and Lean Code-Base Redesign**
   - favour ‘composition’ over ‘inheritance’
   - boosts maintainability and adaptability
   - preserve tried-and-tested functionalities
3. **Performance Optimisations**
   - high-performance, type-strict IO buffers
   - zero-overhead for graphs known at compile-time
   - out-of-the-box hardware acceleration (SIMD, GPU, etc.)
   - optimise linear flow dependency sub-graphs (e.g. avoid/minimise need for buffers)
4. **Tag-Based Timing System Integration** (White Rabbit, GPS, SW-based etc.)
5. **Advanced Processing Features**
   - transactional and multiplexed settings
   - synchronous chunked data processing (for event-based and transient-recording signals)
6. **Broaden Cross-Platform Support** (including WebAssembly)
7. **User-pluggable Work Scheduler Architecture** adaptable to
   - domain (e.g., CPU, GPU, NET, FPGA, DSP, …)
   - scheduling constraints (throughput, latency, …)
8. **Overall project direction**

5. Advanced Processing Features

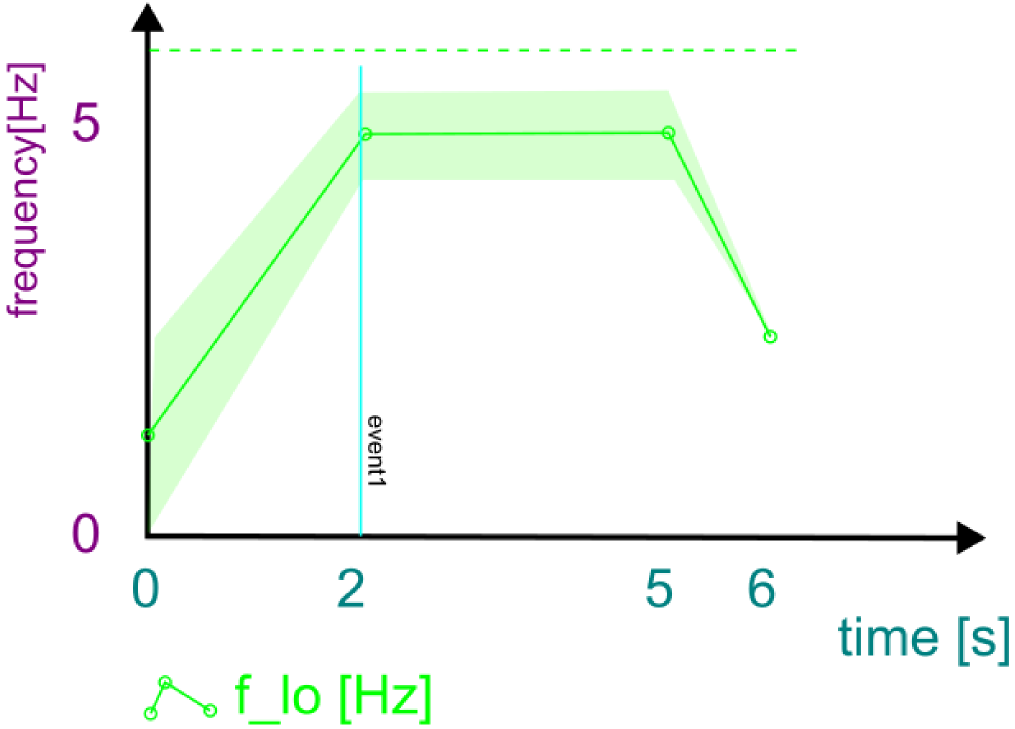
transactional and multiplexed settings – combine sample-by-sample & chunked signal processing

‘FAIR.SELECTOR.C=<BPCID>:S=<SID>:P=<BPID>:T=<GID>’



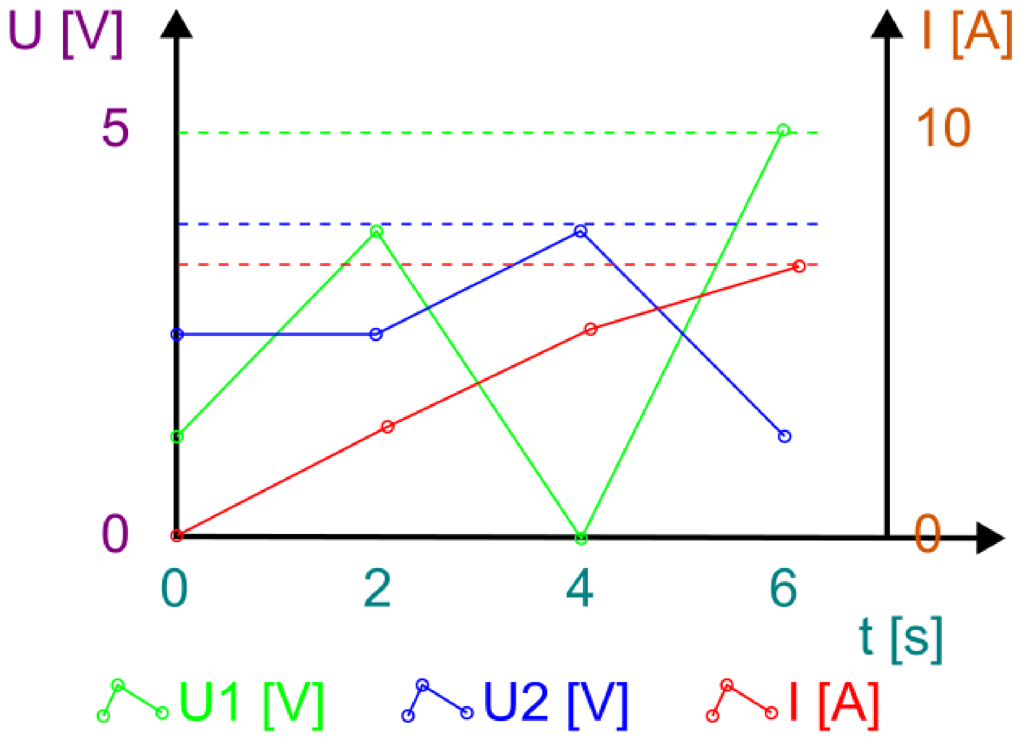
(3) #- - - - DataSet<T> – Example: 1-dim function

```
{
timestamp: 123456789; // [ns]
axis_names: ["time", "frequency"];
axis_units: ["s", "Hz"];
axis_values: [[0, 2, 5, 6], [0, 5]];
extents: [1, 4];
layout: layout_right;
signal_names: ["f_lo"];
signal_units: ["Hz"];
signal_values: [1, 5, 5, 2];
signal_errors: [1, 0.5, 0.5, 0];
signal_ranges: [[0 , 6]];
signal_status: [{"locked": true}];
timing_events: [{123456791: <pmtv>}];
}
```



(3) #- - - - DataSet<T> – Example: N=3 x 1-dim function

```
{
timestamp: 123456789; // [ns]
axis_names: ["t", "U", "I"];
axis_units: ["s", "V", "A"];
axis_values: [[0, 6],[0, 5], [0, 10]];
extents: [3, 4];
layout: layout_right;
signal_names: ["U1", "U2", "I"];
signal_units: ["V", "V", "A"];
signal_values: [
  1,3,0,5,
  2,2,3,1,
  0,2,4,5];
signal_errors: [];
signal_ranges: [[0,5],[0,4],[0,5]];
signal_status: [];
timing_events: [];
}
```



(3) #- - - - DataSet<T> – Example: Image/Matrix/Tensor

```
{
timestamp: 123456789; // [ns]
axis_names: ["x", "y", "\phi"];
axis_units: ["m", "m", "°"];
axis_values: [[0, 4], [0, 2]];
extents: [1, 5, 3];
layout: layout_right;
signal_names: ["T"];
signal_units: ["°"];
signal_values: [
  0, 0, 0, 0, 0,
  0, 2, 3, 2, 0,
  0, 0, 0, 0, 0];
signal_errors: [];
signal_ranges: [0,3];
signal_status: [];
timing_events: [];
}
```