N7 SPACE

C++20 for the Flight Software

Final Presentation

N7 Space

- Company devoted to space systems software development
- Joint venture between SPACEBEL and N7 Mobile
- Key activities:
  - Critical software development for real-time embedded systems
    - LEON and ARM based systems
    - Software qualification based on ECSS standards
  - Development and applications of MBSE tools
    - Formal architecture and data modelling for flight software
    - Model checking
    - Rich experience in TASTE and Capella ecosystems
- Engineering team with ~10 years of experience in space engineering
- Team size: 25

Agenda

- Introduction
- Useful C++ features
- Error handling
- Notable C++20 features
- Compiler support
- C++ Standard Library applicability
- Memory allocation control
- RTOS integration
- Runtime overhead
- Additional tooling
- Coding guidelines

Replacing C operations

How one can improve C code with C++?

- Component reuse and code generalization
- Metaprogramming and compile-time computation
- Deterministic and reliable resource management in C++
- Conditional compilation and reconfigurability.

Replacing C operations- component reuse and code generalization

C- style

- void * casting
- Macro subtitution

void *

≠

Polymorphism

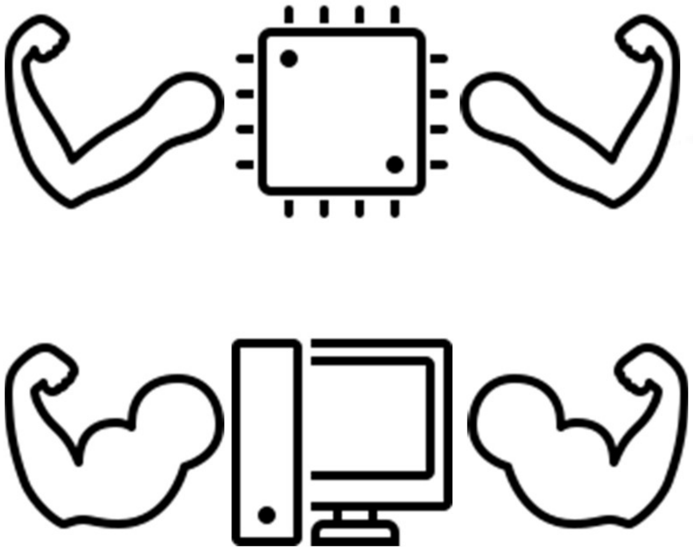
C++- style

- Inheritance
- Polymorphism
  - Static polymorphism
    - Template
    - Overloading
    - CRTP
  - Dynamic polymorphism
    - Overriding

```cpp
void print(int i) { cout << i << "\n"; }
void print(double d) { cout << d << "\n"; }

template <class T> T add(T a, T b) { return a + b;

class Complex {
public:
  double r, i;
  Complex operator+(const Complex &c) {
    return {r + c.r, i + c.i};
  }
};


class Animal{
public:
  virtual void says() = 0;
};

class Cat : public Animal{
public:
  void says() override {
    cout << "Meow!\n";
  }
}
```

Replacing C operations- metaprogramming

- Metaprograming
  - templates
    - Using recursive template instantiation and defining a stop condition as template specialisation
    - Cpp template system is Turing complete. Supposedly that was discovered accidentally
  - constexpr
    - Depending on the arguments can be performed in compile or run time.
  - consteval – immediate functions
    - Can be executed only at compile time
    - Will fail to compile if cannot be executed at compile time
  - constinit
    - enforces a compile time initialization
    - can detect or prevent static initialization order fiasco



Icons by icons8

Replacing C operations- Deterministic and reliable resource management in C++

- Resource Acquisition is initialization- RAII
  - Constructor and destructors
    - Management of resource life cycle.
    - Constructor will allocate a resource for you
    - Destructor will clean a resource for you
  - Copy constructor and copy assignment operator
    - Management of resource copying.
    - Will make a deep copy of the resource if necessary
  - Move constructor and move assignment operator
    - Management of resource ownership

Replacing C operations- Conditional compilation and reconfigurability.

- Pre-processor directives
  - + Can detect OS
  - + Can be used to pass compilation configuration
  - - Doesn’t follow code indentation
  - - Not all of the code is compiled
  - - Doesn’t enforce type safety
- constexpr and constexpr if
  - - can’t detect OS
  - - can’t be used to pass compilation configuration
  - + follows code indentation
  - + all of the code is compiled
  - + enforces static type safety

$$\begin{array}{lcl} \text{constexpr} & & \text{\#ifdef} \\ & > & \\ \text{constexpr if} & & \text{\#elif..} \end{array}$$

```
#ifndef BUF_SIZE // make it possible to pass
                 // compilation configuration
#define BUF_SIZE 32u
#endif

namespace example
{ // enforce type-safety  with cpp constexpr
constexpr std::size_t buf_size = BUF_SIZE;
} // namespace example
char buf[example::buf_size];
```

Error handling

- Many approaches to error handling
  - Error codes
  - errno
  - Error handlers
  - `goto` – please don't
  - exceptions

Exceptions vs error codes

- Binary size overhead
- Runtime overhead on happy and error paths
- Readability
- Usability
- Default safety
- Composability

Recommendations

- Exceptions either disabled or used for critical failures
  - This recommendation in specifically targeting real time software
- Mark reusable public interface as `noexcept`
  - Even with exceptions disabled

C++20: Coroutines

- Resumable functions
  - Can simplify complex state machines
- Currently expert-friendly
  - Minimal support from the Standard Library
  - Depends on heap allocation (by default)
- Work quite well with RTEMS SMP QDP’s GCC

C++20: Modules

- Probably the largest change to the language in years
  - Changes decades-old compilation model
- Isolation from accidental macros
- Better encapsulation built-in
  - Explicit export control
- Accidental ODR bugs are harder to introduce
- Compile time improvement potential is a nice bonus
- Header units as a middle ground
- `import std;` in C++23
- Not ready for use yet
  - Lots of fixes in Clang and GCC since we finished our report
  - Best practices still need to be formulated
  - Header files are not going anywhere

Compiler support

Toolchain support

ARM

- Can be created from sratch based on GCC or Clang with GNU otr LLVM libs
- ARM Ltd
- Linaro
- Vendor specific e.x.:
    - STM32
    - Microchip

Sparc

- Can be created from sratch based on GCC or Clang with GNU otr LLVM libs
- Frontgrade Gaisler
    - BCC2
        - LEON 2-5
        - GNU and LLVM
        - C++11 support
        - Some features of C++ ver. up to 20 should be supported
    - BCC
        - LEON 3,4
        - GNU based

RISC-V

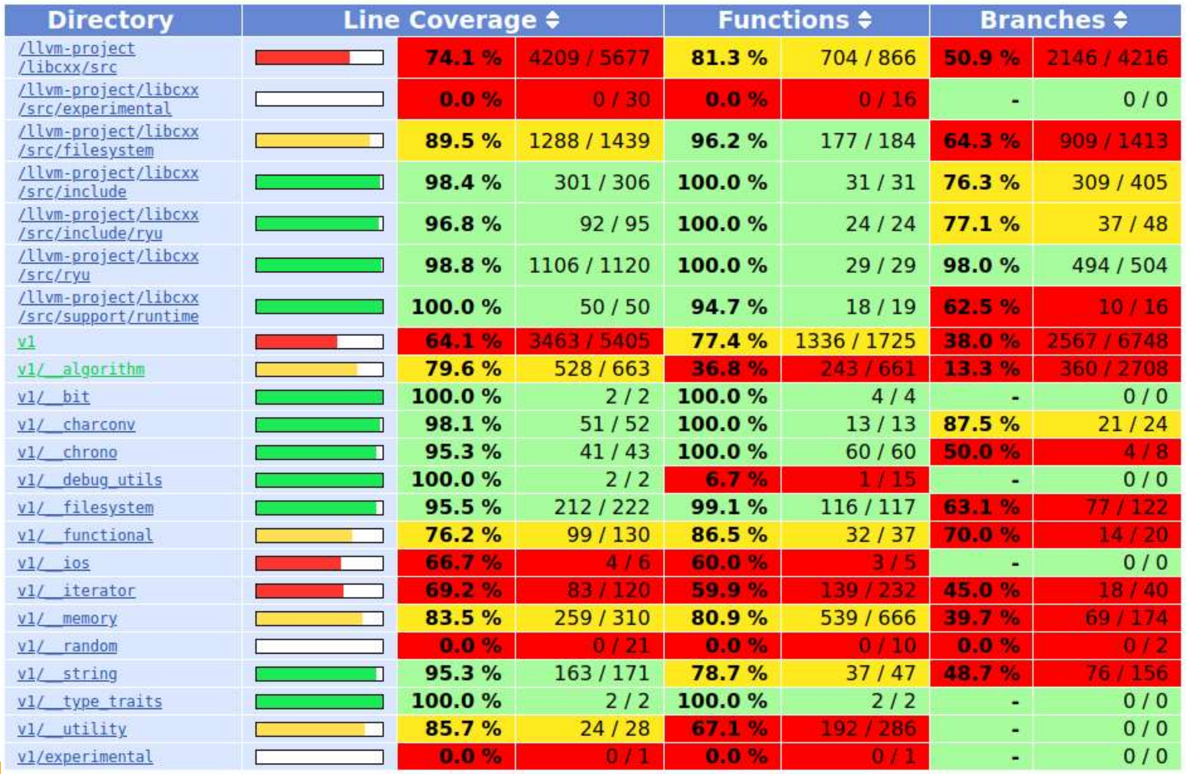
- Can be created from sratch based on GCC or Clang with GNU otr LLVM libs
- SiFive
- RISC-V International
- PlatformIO Labs
- Embecosm
- Yocto

Validation of standard library

libc++, version 15	libstdc++, version 12.2.0
Full support up to C++14, partial of C++17 and 20	Full support up to C++17, partial of C++20
Documentation: available online and possible to generate on request using CMake	Documentation: available online and possible to generate on request using Doxygen
License: Apache 2	License: GNU General Public License (GPL) v3 with the GCC Runtime Library Exception
Nesting level over 5: 18 offenders	Nesting level over 5: 75 offenders
Cyclomatic complexity over 15: 48 offenders	Cyclomatic complexity over 15: 217 offenders

Validation of standard library coverage

libc++



Directory	Line Coverage ⬍			Functions ⬍		Branches ⬍	
/llvm-project/libcxx/src	🟥	74.1 %	4209 / 5677	81.3 %	704 / 866	50.9 %	2146 / 4216
/llvm-project/libcxx/src/experimental	⬜	0.0 %	0 / 30	0.0 %	0 / 16	-	0 / 0
/llvm-project/libcxx/src/filesystem	🟨	89.5 %	1288 / 1439	96.2 %	177 / 184	64.3 %	909 / 1413
/llvm-project/libcxx/src/include	🟩	98.4 %	301 / 306	100.0 %	31 / 31	76.3 %	309 / 405
/llvm-project/libcxx/src/include/ryu	🟩	96.8 %	92 / 95	100.0 %	24 / 24	77.1 %	37 / 48
/llvm-project/libcxx/src/ryu	🟩	98.8 %	1106 / 1120	100.0 %	29 / 29	98.0 %	494 / 504
/llvm-project/libcxx/src/support/runtime	🟩	100.0 %	50 / 50	94.7 %	18 / 19	62.5 %	10 / 16
v1	🟥	64.1 %	3463 / 5405	77.4 %	1336 / 1725	38.0 %	2567 / 6748
v1/__algorithm	🟨	79.6 %	528 / 663	36.8 %	243 / 661	13.3 %	360 / 2708
v1/__bit	🟩	100.0 %	2 / 2	100.0 %	4 / 4	-	0 / 0
v1/__charconv	🟩	98.1 %	51 / 52	100.0 %	13 / 13	87.5 %	21 / 24
v1/__chrono	🟩	95.3 %	41 / 43	100.0 %	60 / 60	50.0 %	4 / 8
v1/__debug_utils	🟩	100.0 %	2 / 2	6.7 %	1 / 15	-	0 / 0
v1/__filesystem	🟩	95.5 %	212 / 222	99.1 %	116 / 117	63.1 %	77 / 122
v1/__functional	🟨	76.2 %	99 / 130	86.5 %	32 / 37	70.0 %	14 / 20
v1/__ios	🟥	66.7 %	4 / 6	60.0 %	3 / 5	-	0 / 0
v1/__iterator	🟥	69.2 %	83 / 120	59.9 %	139 / 232	45.0 %	18 / 40
v1/__memory	🟨	83.5 %	259 / 310	80.9 %	539 / 666	39.7 %	69 / 174
v1/__random	⬜	0.0 %	0 / 21	0.0 %	0 / 10	0.0 %	0 / 2
v1/__string	🟩	95.3 %	163 / 171	78.7 %	37 / 47	48.7 %	76 / 156
v1/__type_traits	🟩	100.0 %	2 / 2	100.0 %	2 / 2	-	0 / 0
v1/__utility	🟨	85.7 %	24 / 28	67.1 %	192 / 286	-	0 / 0
v1/experimental	⬜	0.0 %	0 / 1	0.0 %	0 / 1	-	0 / 0

libstdc++

Directory	Line/Statement coverage	Decision coverage
libstdc++ include/	91.6%	57.6%
libstdc++ include/bits/	88.0%	55.1%
libstdc++ src/	72.1%	50.4%

Dynamic allocation in the Standard Library

- Different parts of the Standard Library have different approaches to allocating memory
  - Some do not allocate at all (`std::array<>`, `std::tuple<>`, `std::variant<>`, `std::optional<>`, `std::atomic<>`)
  - Some may allocate depending on the size of stored data (`std::any`, `std::function<>`, `std::string`)
  - Some data structures allow control (`std::vector<>`, `std::list<>`, `std::string`)
  - Most algorithms do not allocate, but some need to
  - Some parts are of no interest in flight software (IO, regular expressions, OS-based thread or filesystem support)
- Inconsistent approach, requires knowledge/documentation

Custom allocators for Standard Library containers

```
template <class T>
class simple_allocator {
public:
  using value_type = T;

  simple_allocator() = default;
  template <class U>
  simple_allocator(const simple_allocator<U> &) noexcept;

  [[nodiscard]] T *allocate(const std::size_t n);
  void deallocate(T *, const std::size_t n) const noexcept;

private:
  static T static_memory_pool[SIMPLE_ALLOC_POOL_SIZE];
  static std::size_t m_pool_counter;
};

template <class T, class U>
bool operator==(const simple_allocator<T> &,
                const simple_allocator<U> &) noexcept;
template <class T, class U>
bool operator!=(const simple_allocator<T> &,
                const simple_allocator<U> &) noexcept;
```

```
std::vector<int, simple_allocator<int>> vec{1, 2, 3,
4, 5};

vec.push_back(6);
vec.push_back(7);
vec.push_back(8);
vec.clear();
```

```
static char buffer[BUF_SIZE];
std::pmr::monotonic_buffer_resource alloc{buffer, BUF_SIZE};

std::pmr::pool_options options;
options.max_blocks_per_chunk = 32;
options.largest_required_pool_block = 512;
std::pmr::unsynchronized_pool_resource pool{options, &alloc};

std::pmr::vector<int> vec{&pool};

vec.push_back(6);
vec.push_back(7);
vec.push_back(8);
```

Custom allocation in other places

- Emergency pool for exceptions
  - Can be controlled in recent GCC versions
- Overriding `new/delete` operators
  - Useful for logging and tracking unwanted memory operations
- Garbage collection
  - Abandoned

RTOS compatiblity

- Investigation into C++ compability with popular RTOSes
  - Only RTEMS SMP QDP investigated
- Multiple examples produced with a dockerized CMake build-system integrating RTEMS SMP QDP
- No functional compatibility issues discovered – it just works
- Schedulability analysis issues
  - Exceptions
  - RTTI
  - Heap allocation

C++ support for RTEMS concurrency

- `std::mutex`, `std::condition_variable` can be made to work
  - But require the not-qualified POSIX API
- `std::shared_mutex` and `std::shared_lock` do not work
- Latches and Barriers are not compatible with the Barrier Manager

but

- `std::atomic<>` and the `<atomic>` standard header supported and recommended
- RTEMS mutex and condition variable can be easily wrapped in C++ Standard Library compatible interface
- Other locking RAII types (e.g. `std::unique_lock`) work with C++ wrappers over RTEMS primitives

C++ support for RTEMS concurrency

```
class RtemsMutex {
public:
  RtemsMutex(rtems_name name);
  ~RtemsMutex();
  // not copyable, not moveable
  RtemsMutex(const RtemsMutex &) = delete;
  RtemsMutex &operator=(const RtemsMutex &) = delete;
  const rtems_id &getId() const { return m_id; }
  void obtain();
  void release();
  // meet BasicLockable requirements
  void lock() { obtain(); }
  void unlock() { release(); }
  // meet Lockable requirements
  bool try_lock();
private:
  rtems_id m_id;
};
```

```
std::deque<int> sharedResource;
RtemsMutex mutex{rtems_build_name('M', 'T', 'X', '0')};

void produce(const int val) {
  std::scoped_lock lock(mutex);
  sharedResource.push_front(val);
} // unlock mutex in destructor

int consume() {
  std::scoped_lock lock(mutex);
  if (!m_sharedResource.empty()) {
    const int val = sharedResource.back();
    sharedResource.pop_back();
    return val;
  }
  return -1;
} // unlock mutex in destructor
```

Runtime overhead

- Investigation into runtime overhead of C++ constructs over C analogues

- Namespaces: no overhead
- Type conversions:
  - Possible overhead of implicit conversions of large types
  - Overhead in dynamic type conversions (RTTI, `typeid` and `dynamic_cast<>`)
- Function calls: no overhead
- Virtual dispatch:
  - Slight overhead over non-virtual functions, insignificant for non-trivial functions
  - Same as calling through function pointer
- Exceptions: nominal path is zero-cost in most implementations

Runtime overhead – ring buffer

```cpp
template <typename T, std::size_t CAPACITY>
class rb_queue {
  std::array<T, CAPACITY> buffer;
public:
  using value_type = T;
  using size_type = std::size_t;
  /* Construction/destruction */
  rb_queue() = default;
  ~rb_queue() = default;
  /* Element access */
  T front() const;
  T back() const;
  /* Capacity */
  size_type capacity() const;
  size_type size() const;
  bool full() const;
  bool empty() const;
  /* Modifiers */
  void push(const T &value);
  void pop();
};
```

```c
typedef int rb_queue_value_type;
/* Construction/destruction */
void rb_queue_init(rb_queue *q, rb_queue_value_type
                   buffer[], size_t capacity);
void rb_queue_destroy(rb_queue *q);
/* Element access */
rb_queue_value_type rb_queue_front(const rb_queue *const q);
rb_queue_value_type rb_queue_back(const rb_queue *const q);
/* Capacity */
bool rb_queue_empty(const rb_queue *q);
bool rb_queue_full(const rb_queue *q);
size_t rb_queue_capacity(const rb_queue *q);
size_t rb_queue_size(const rb_queue *const q);
/* Modifiers */
void rb_queue_push(rb_queue *q, rb_queue_value_type val);
void rb_queue_pop(rb_queue *q);
```

Runtime overhead – Standard Library

- Tons of standard algorithms in C++ Standard Library, only 2 in C
- Binary search
    - Not much difference, `std::lower_bound` can benefit from inlining the comparator, but there isn't a lot of comparisons is $O(\log_2 N)$
- Sorting
    - `std::sort` is considerably faster than `qsort`
    - But adds a noticeable amount of code for each instantiation

Tools

- Most tools that target C++, support C as well
- Some tools can be used on target hardware
- And some require running on development machines
  - Additional x86 build for flight software is highly recommended
- Adherence to a coding standard
- Important for correctness

Tools

- Static analysers
  - Compiler warnings (first line of defense)
  - Free linters and path sensitive analysers (*clang-tidy*, *cpplint*, *clang-sa*, *cppcheck*)
  - Commercial software
- Dynamic analysers (*sanitizers* and *valgrind*)
  - Critical for finding memory correctness and concurrency bugs
- Debuggers
- Profilers (*vTune*, *WPA*, *perf_events*, *optick*, *valgrind*, manual instrumentation etc.)
  - A convenient profiler for target hardware would be nice…
- Code formatters
- `#include` analysers (*include-what-you-use*, *cppinclude*, *clangd*'s *includecleaner*)
  - Even when modules are stable, header files will stay for decades
- Build systems
- Documentation generators
- Unit testing frameworks

Tools – ECSS-E-ST-40C Annex U

- 14 common-sense rules
- Recommended in the ECSS standard
- All enforceable using free tools from previous slide

- The code does not include any infinite loops…
    - Let’s solve the halting problem first ;)
    - In practice simple infinite loops are easily detected by tools

C++ Core Guidelines

- Living document, not versioned in practice
- Guidelines Support Library
- Rule investigation and tailoring for space projects
    - Exceptions
    - Dynamic memory allocation
    - GSL use

CISQ ISO/IEC 5055:2021

- Code Quality Standards
- ~140 rules based on CWEs
- Measures software quality
- 4 main pillars:
  - Reliability
  - Security
  - Performance efficiency
  - Maintainability
- Reviewed all rules and proposed alternative tailoring

AUTOSAR C++

- Based on MISRA C++:2008
  - Original is too old to be applicable for modern language revisions
  - Updated for C++14 with some C++17 rules, if available
- Obsolete since 2019
  - But still very useful (until recently)
- High tool coverage
  - Only commercial offerings
- Rule investigation and tailoring for space projects
  - Exceptions
  - Dynamic memory allocation

Minimal C++20 for Flight Software Coding Guidelines

- None of investigated standards were up-to-date
- Common sense rules enforceable using free tools
    - With flight-themed examples
    - With traceability to AUTOSAR C++, MISRA C++, C++ Core Guidelines, SEI CERT C++ rules
    - Enforceable using free tools
    - Annex U rules taken into account
    - Attached `clang-tidy` configuration file
- 43 general guidelines
- 5 guidelines related to dynamic memory allocation

MISRA C++:2023

- Investigation planned, not performed
- Merge of AUTOSAR C++ into MISRA
  - Updated for C++17
- Internally reviewed after available publicly
  - Tooling not there yet
  - We plan to use it in one of our projects
  - The way to go in the future

Conclusions

- Newer C++ revisions as viable as older ones
- But some new features do not have complete implementation yet
  - Mainly modules
- Partial prequalification of the Standard Library would be useful
  - Vocabulary types, some algorithms
  - Alternatively, ETL or some other reusable library
- Compile-time computation can only be covered indirectly
  - Does not produce object code to execute
- Avoid after initialization or always
  - Exceptions
  - RTTI
  - Heap

Thank you for your attention

Jakub Rachucki
jrachucki@n7space.com
Wojciech Cierpucha
wcierpucha@n7space.com
www.n7space.com

Example1: templates generalization

```
size_t ser(uint8_t *buf, const size_t bufSize,     //
           const size_t offset,                    //
           const void *val, const size_t valSize) //
{
  size_t resultIdx = offset;

  if (bufSize >= offset + valSize)
  {
    memcpy(&buf[offset], val, valSize);
    resultIdx += valSize;
  }
  /*.. else() etc*/
  return resultIdx;
}

/*..*/
constexpr size_t SIZE = 10;
uint8_t buf[SIZE];
float val = 3.14;
```

Example1: templates generalization

```
size_t ser(uint8_t *buf, const size_t bufSize,     //
           const size_t offset,                    //
           const void *val, const size_t valSize) // Function doesn't know the type nor its size
{
  size_t resultIdx = offset;

  if (bufSize >= offset + valSize)
  {
    memcpy(&buf[offset], val, valSize);
    resultIdx += valSize;
  }
  /*.. else() etc*/
  return resultIdx;
}

/*..*/
constexpr size_t SIZE = 10;
uint8_t buf[SIZE];
float val = 3.14;
ser(buf, SIZE, 1, &val, sizeof(val)); // User needs to remember to call sizeof or need to know the size
```

Example1: templates generalization

```
size_t ser(uint8_t *buf, const size_t bufSize,     // Can we trust that a user will pass proper size values?
           const size_t offset,                    //
           const void *val, const size_t valSize) // Function doesn't know the type nor its size
{
  size_t resultIdx = offset;

  if (bufSize >= offset + valSize)
  {
    memcpy(&buf[offset], val, valSize);
    resultIdx += valSize;
  }
  /*.. else() etc*/
  return resultIdx;
}

/*..*/
constexpr size_t SIZE = 10;
uint8_t buf[SIZE];
float val = 3.14;
ser(buf, SIZE, 1, &val, sizeof(val)); // User needs to remember to call sizeof or need to know the size
```

Example1: templates generalization

```
template <typename T>
size_t serCpp(span<uint8_t> buf, // Buffer size deduced by span
              const size_t idx,  //
              const T val)       // Type deduced by a compiler
{
  constexpr size_t bytesNum = sizeof(T); // Size always calculated by compiler
  size_t resultIdx = idx;
  if (buf.size() >= bytesNum + idx)
  {
    span<uint8_t> destination = buf.subspan(idx);
    const T source = val;
    std::memcpy(destination.data(), &source, bytesNum);
    resultIdx += bytesNum;
  }
  /*.. else() etc*/
  return resultIdx;
}

/*..*/
constexpr size_t SIZE = 10;
uint8_t buf[SIZE];
float val = 3.14;
serCpp(buf, 1, &val); // User don't care about calling sizeof or remembering the size
```

Example2: compile time facility

```
template <int N> struct fact
{
  enum
  {
    val = fact<N - 1>::val * N
  };
};

template <> struct fact<0>
{
  enum
  {
    val = 1
  };
};

int main()
{
  std::printf("5! = %d\n",
fact<5>::val);
  return 0;
}
```

Example2: compile time facility

```cpp
template <int N> struct fact
{
  enum
  {
    val = fact<N - 1>::val * N
  };
};

template <> struct fact<0>
{
  enum
  {
    val = 1
  };
};

int main()
{
  std::printf("5! = %d\n",
fact<5>::val);
  return 0;
}
```

```cpp
constexpr int fact(const int v)
{
  int result = 1;
  for (int i = 1; i <= v; ++i)
  {
    result *= i;
  }
  return result;
}

int main()
{
  int x = 5;
  int f5 = fact(x);
  constexpr int f6 = fact(6);
  std::printf("5! = %d\n", f5);
  std::printf("6! = %d\n", f6);
  return 0;
}
```

Example2: compile time facility

```
template <int N> struct fact
{
  enum
  {
    val = fact<N - 1>::val * N
  };
};

template <> struct fact<0>
{
  enum
  {
    val = 1
  };
};

int main()
{
  std::printf("5! = %d\n",
fact<5>::val);
  return 0;
}
```

```
constexpr int fact(const int v)
{
  int result = 1;
  for (int i = 1; i <= v; ++i)
  {
    result *= i;
  }
  return result;
}

int main()
{
  int x = 5;
  int f5 = fact(x);
  constexpr int f6 = fact(6);
  std::printf("5! = %d\n", f5);
  std::printf("6! = %d\n", f6);
  return 0;
}
```

```
consteval int fact(const int v)
{
  int result = 1;
  for (int i = 1; i <= v; ++i)
  {
    result *= i;
  }
  return result;
}

int main()
{
  // int x = 5;
  // int f5 = fact(x);
  constexpr int f6 = fact(6);
  // std::printf("5! = %d\n", f5);
  std::printf("6! = %d\n", f6);
  return 0;
}
```

Example3: CRTP

```
template <typename Derived> class Animal
{
public:
  void says() { static_cast<Derived *>(this)->saysImpl(); }
  void saysImpl() { cout << "Base implementation\n"; }
};

class Fox : public Animal<Fox>
{
public:
  void saysImpl() { cout << "Wa-pa-pa-pow\n"; }
};
```

Example4: Static init. fiasco

```
// Fiasco
// File1.cpp
extern int get_value();

int globVar1 = get_value();
int get_value() { return 42; }

// File2.cpp
extern int globVar1;
int globVar2 = globVar1 + 1;

int main()
{
  cout << "globVar2: " << globVar2 << "\n";
// May not be 43
  return 0;
}
```

```
// Constinit solution
// File1.cpp
extern int get_value();
constinit int globVar1 = get_value();
// Init at compile time
int get_value() { return 42; }

// File2.cpp
extern constinit int globVar1;
constinit int globVar2 = globVar1 + 1;
// Initialized at compile time
int main()
{
  cout << "globVar2: " << globVar2 << "\n";
// Guaranteed to be 43
  return 0;
}
```