Concepts for designing modern C++ interfaces for MPI

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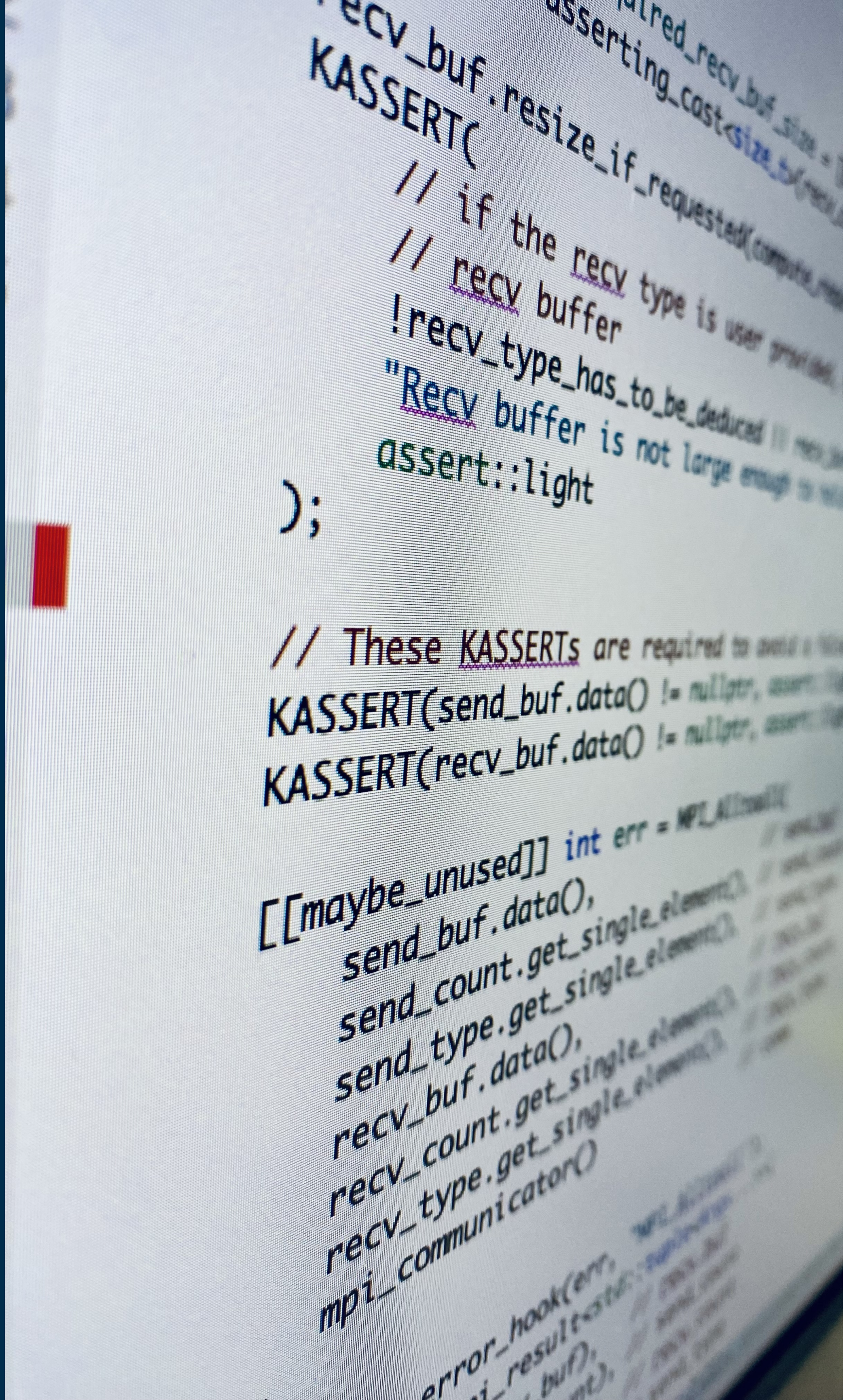
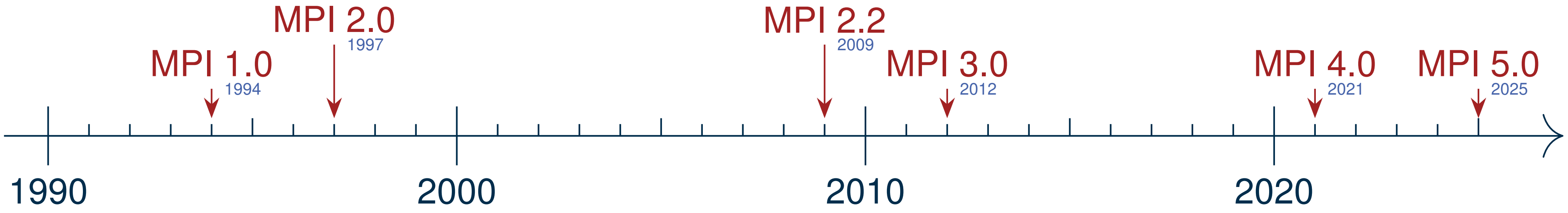
EuroMPI/USA'25, Charlotte, NC | October 2, 2025



A Brief History of MPI and C++



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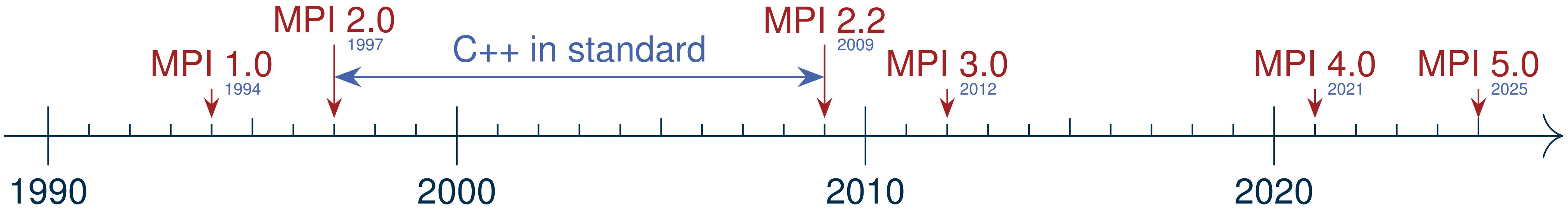

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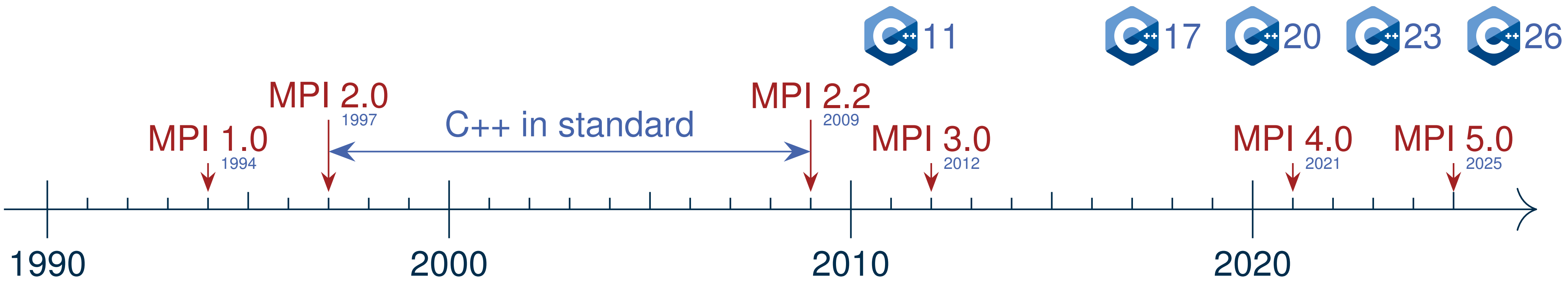

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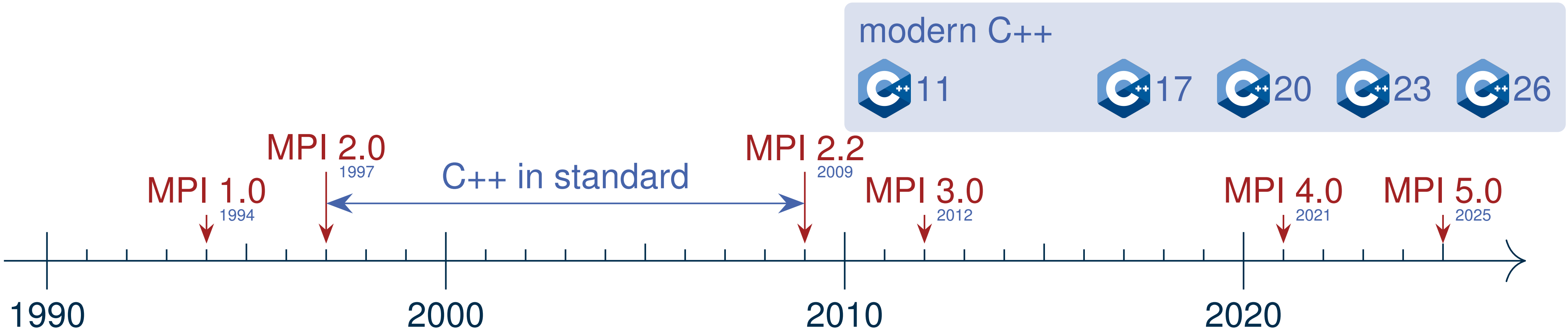

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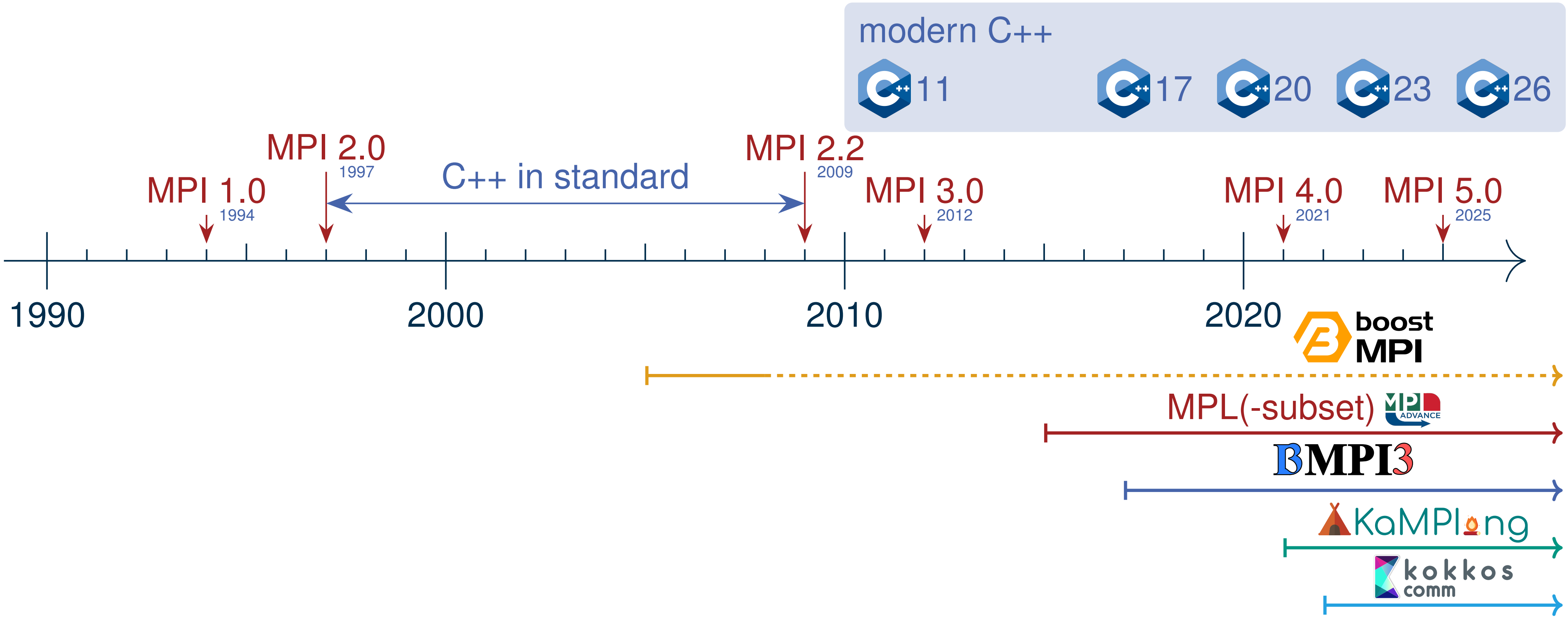

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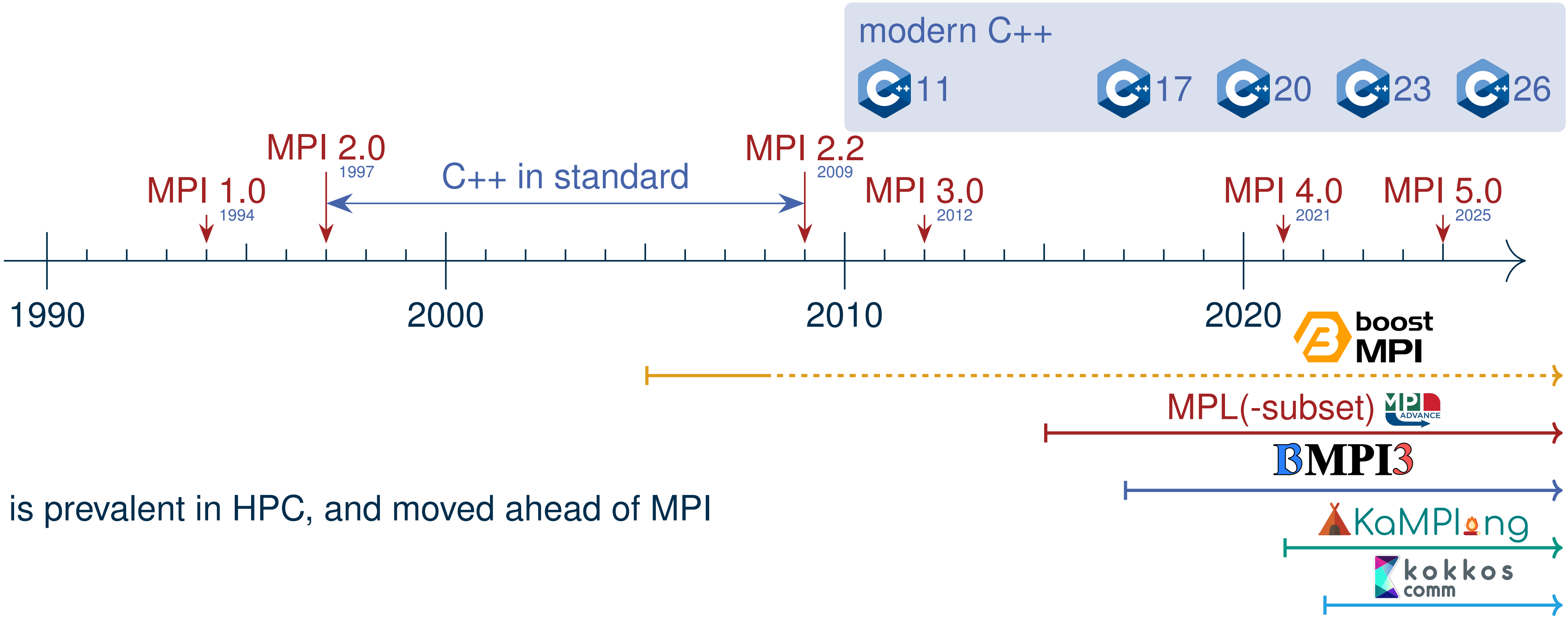

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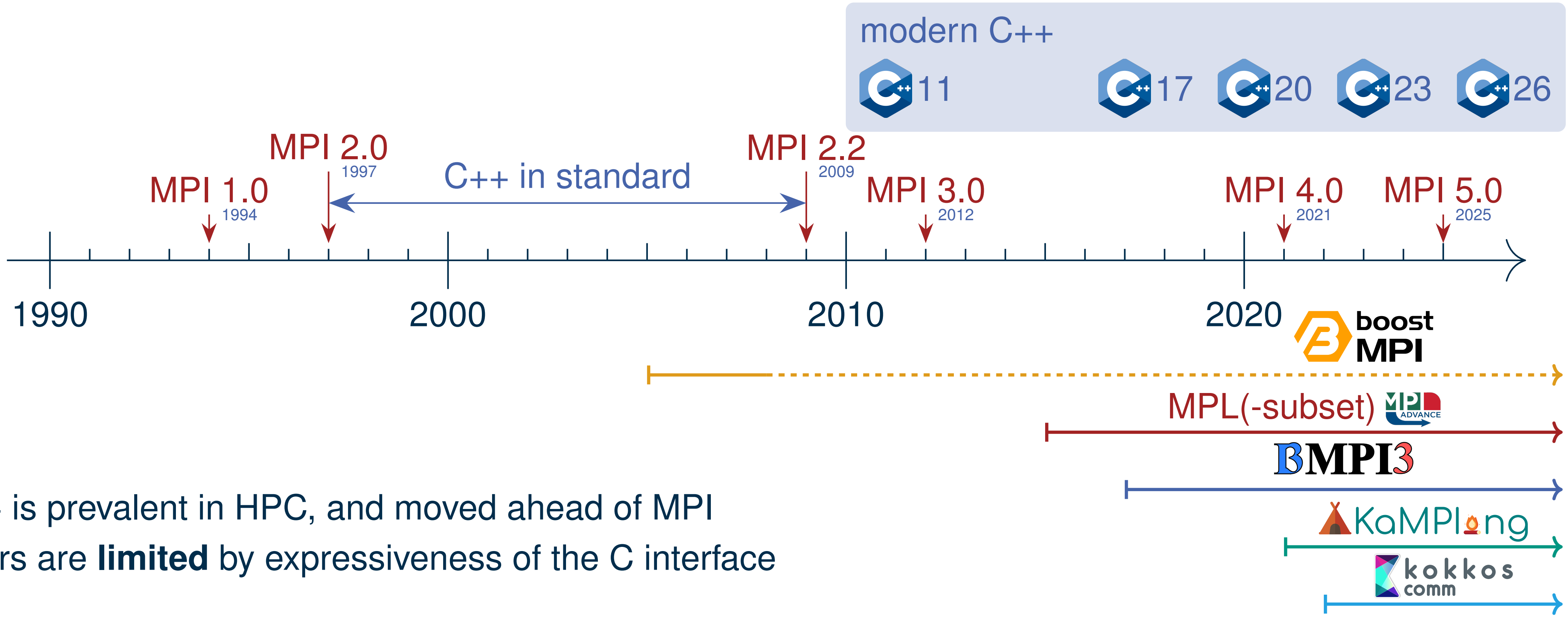

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- Users are **limited** by expressiveness of the C interface

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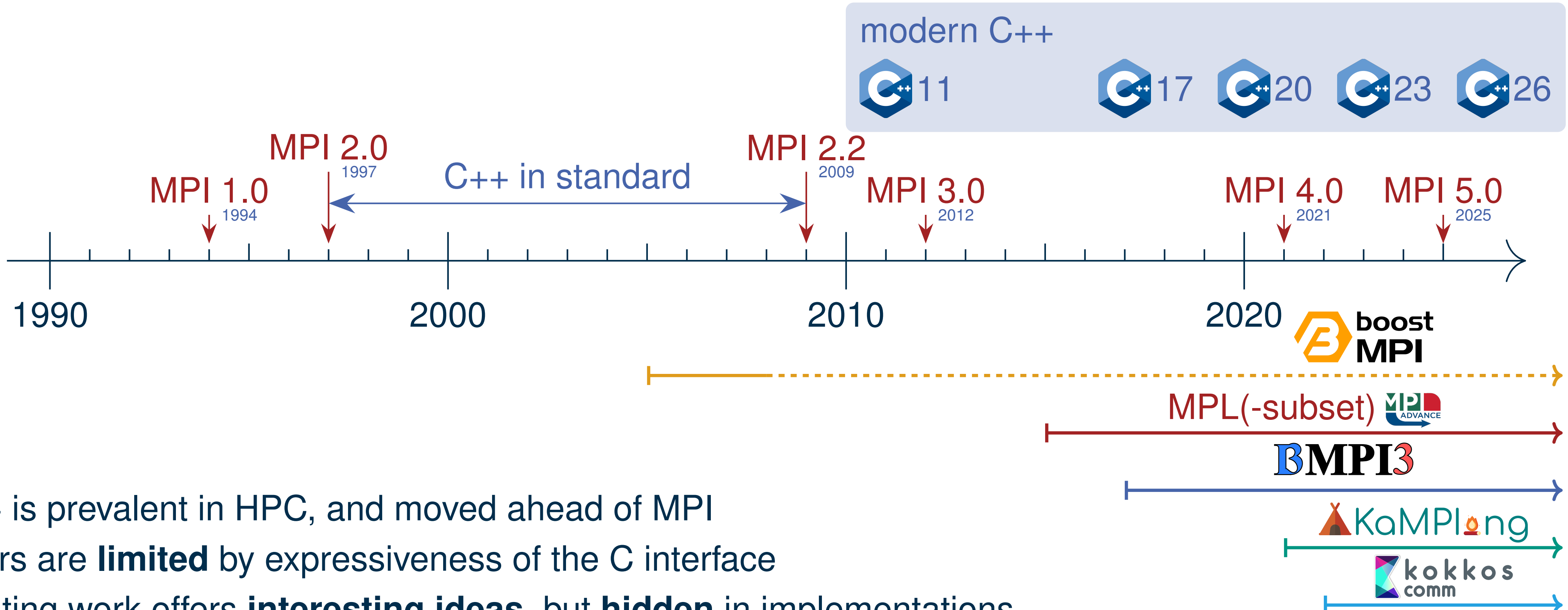

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- Existing work offers **interesting ideas**, but **hidden** in implementations

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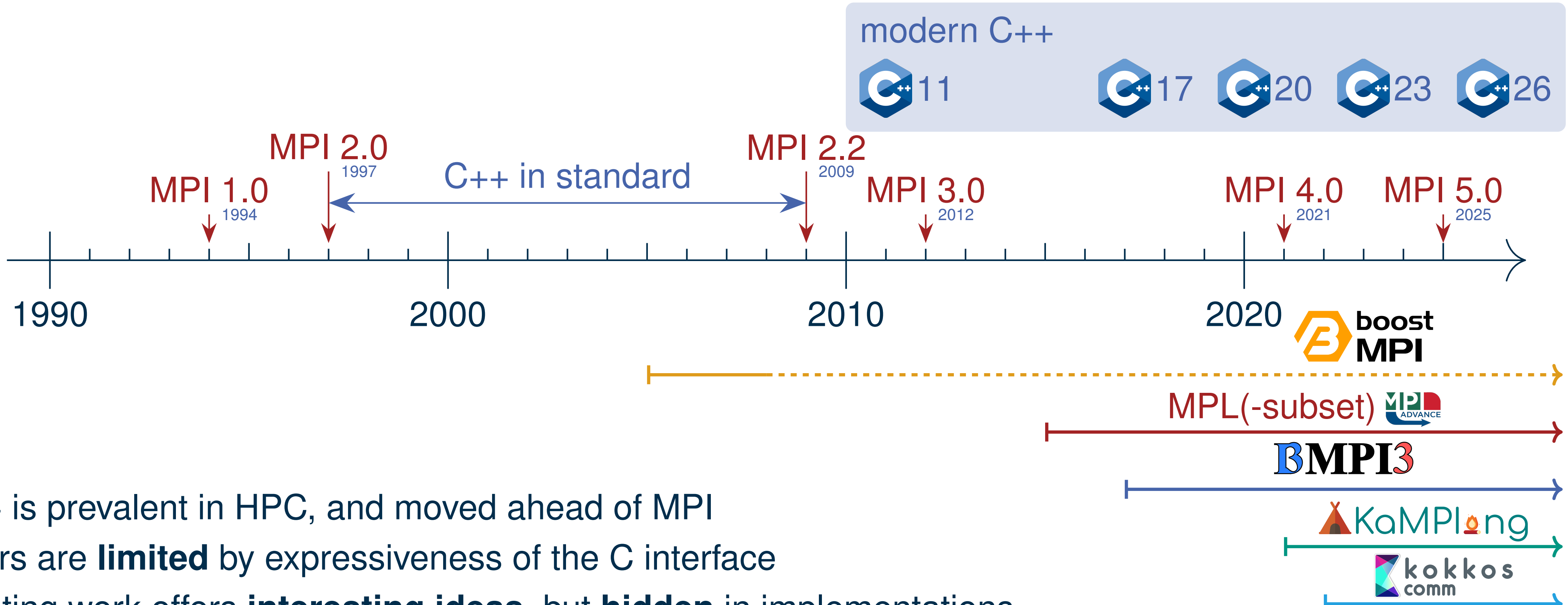

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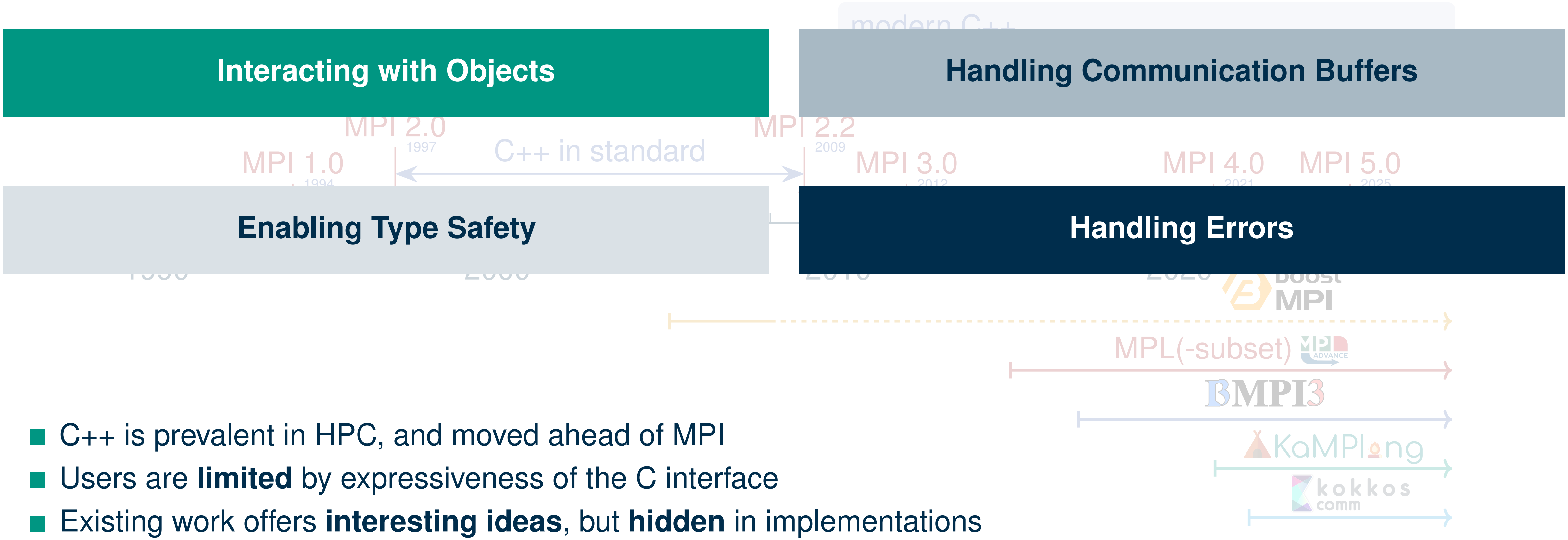
- Existing work offers **interesting ideas**, but **hidden** in implementations
- **Our goal:** define **semantic concepts** to **bridge** MPI and idiomatic C++

A Brief History of MPI and C++

Interacting with Objects | **Handling Communication Buffers**

Enabling Type Safety | **Handling Errors**



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- MPI users interact with **objects**
  - communicators, data types, requests, groups, info objects, . . .
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  - ... and move semantics

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```
class Comm {
public:
  Comm(Comm const &other, Group const &group) {
    MPI_Comm_create(other.handle(), group.handle(), &comm_);
  }
  Comm(Comm &&other) { ... }
  operator=(Comm && other) { ... }
  ~Comm() { MPI_Comm_free(&comm_); }
private:
  MPI_Comm comm_;
};
```

Modeling Objects

```cpp
class Comm {...};
```

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```cpp
class Comm {...};

auto construct() {
  mpi::Comm comm{parent_comm, group};
  return comm;
}

void foobar(mpi::Comm comm) {
  // ...
  // comm gets freed at
  // end of scope
}

auto comm = construct();
foobar(std::move(comm));
```

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  - but that sometimes conflicts with MPI's implicit global state

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  - ... and move semantics
  - but that sometimes conflicts with MPI's implicit global state
- **session model** aligns well with object oriented design

```
MPI_Session session = MPI_SESSION_NULL;
MPI_Session_init(MPI_INFO_NULL,
                 MPI_ERRORS_RETURN, &session);
MPI_Group group = MPI_GROUP_NULL;
MPI_Group_from_session_pset(session,
                            "mpi://WORLD", &group);
MPI_Comm comm = MPI_COMM_NULL;
MPI_Comm_create_from_group(group,
                           "org.example",
                           MPI_INFO_NULL,
                           MPI_ERRORS_RETURN, &comm);
MPI_Group_free(&group);
// ...
MPI_Comm_free(&comm);
MPI_Session_finalize(&session);
```

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  - ... and move semantics
  - but that sometimes conflicts with MPI's implicit global state
- **session model** aligns well with object oriented design

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MPI_Session session = MPI_SESSION_NULL;
MPI_Session_init(MPI_INFO_NULL,
                 MPI_ERRORS_RETURN, &session);
MPI_Group group = MPI_GROUP_NULL;
MPI_Group_from_session_pset(session,
                            "mpi://WORLD", &group);
MPI_Comm comm = MPI_COMM_NULL;
MPI_Comm_create_from_group(group,
                           "org.example",
                           MPI_INFO_NULL,
                           MPI_ERRORS_RETURN, &comm);
MPI_Group_free(&group);
// ...
MPI_Comm_free(&comm);
MPI_Session_finalize(&session);
```

```cpp
mpi::Session session;
mpi::Comm comm = session.group_from_pset("mpi://WORLD")
                        .create_comm("org.example");
```

Modeling Data

Safe Type Mapping

`void`
`std::nullptr_t`

`float`
`double`
`long double`

`char`

`signed char`
`unsigned char`
`short int`
`unsigned short int`
`int`
`unsigned int`
`long int`
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`long long int`
`unsigned long long int`
`bool`
`char`

Modeling Data

Safe Type Mapping

fundamental types

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Modeling Data

Safe Type Mapping

MPI data types

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Modeling Data

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MPI_Type_contiguous
MPI_Type_vector
MPI_Type_create_hvector
MPI_Type_indexed
MPI_Type_create_hindexed
MPI_Type_create_struct
MPI_Type_create_subarray

Modeling Data

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MPI data types

fundamental types

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float
double
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char
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```

```
std::array<int, 3>
```

```
double[5]
```

```
enum class MyEnum {...};
```

```
struct MyType {
  int a;
  std::array<int, 3> b;
  double c;
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};
```

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```

Modeling Data

Safe Type Mapping

MPI data types

fundamental types

```
template<typename T, size_t N>
struct type_traits<std::array<T, N>> {
  static MPI_Datatype type() {
    MPI_Datatype type;
    MPI_Type_contiguous(N,
      type_traits<T>::type(),
      &type);
    return type;
  }
};
```

```
float
double
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```
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Modeling Data

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MPI_Type_contiguous
MPI_Type_vector
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MPI_Type_indexed
```

```
template<>
struct type_traits<MyType> {
  static MPI_Datatype type() {
    MPI_Datatype type;
    // get type and disp for each member
    MPI_Type_create_struct(...);
    MPI_Type_create_resized(...);
    return type;
  }
}
```

Modeling Data

Safe Type Mapping

fundamental types

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```

trivially copyable types

`std::array<int, 3>`

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MPI data types

MPI_Type_contiguous
MPI_Type_vector
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Modeling Data

Safe Type Mapping

MPI data types

trivially copyable types

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- `MPI_Type_create_hindexed`
- `MPI_Type_create_struct`
- `MPI_Type_create_subarray`

Modeling Data

Handling Memory Buffers

```
std::vector<int> v = {...};
MPI_Sendrecv(v.data(), v.size(), MPI_INT, dest, ...);
```

Modeling Data

Handling Memory Buffers

```
template<typename T>
int sendrecv(std::vector<T> const& s, int dest, ...) {
  return MPI_Sendrecv(s.data(), s.size(), MPI_INT, dest, ...);
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Problem: ad-hoc, limited to a fixed set of containers → **Solution:** define general concepts

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int MPI_Sendrecv(const void *sendbuf,
                 int sendcount,
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                 int dest,
                 int sendtag,
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```

send buffer

recv buffer

Modeling Data

Handling Memory Buffers

```
template<DataBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
  return MPI_Sendrecv(s.data(), s.size(), MPI_INT, dest, ...);
}
```

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send buffer

recv buffer

```
template <typename T>
concept DataBuffer =
```

Modeling Data

Handling Memory Buffers

```
template<DataBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
  return MPI_Sendrecv(std::ranges::data(s), s.size(), MPI_INT, dest, ...);
}
```

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int MPI_Sendrecv(const void *sendbuf,
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send buffer

recv buffer

```
template <typename T>
concept DataBuffer =
  std::ranges::contiguous_range<T>;
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Handling Memory Buffers

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Handling Memory Buffers

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template<DataBuffer SendBuf>
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```

send buffer

recv buffer

```
template <typename T>
concept DataBuffer =
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  std::ranges::sized_range<T> && mpi::Typed<T>;
```

Modeling Data

Handling Memory Buffers

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template<SendBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
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send buffer

recv buffer

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template <typename T>
concept SendBuffer =
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Handling Memory Buffers

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concept SendBuffer =
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template <typename T>
concept RecvBuffer =
  DataBuffer<T> &&
  std::ranges::output_range<T,
       std::ranges::range_value_t<T>>;
```

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Handling Memory Buffers

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template<SendBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
  return MPI_Sendrecv(std::ranges::data(s), std::ranges::size(s), mpi::type(s), dest, ...);
}
```

Problem: ad-hoc, limited to a fixed set of containers → **Solution:** define general concepts

```
template <typename Buf>
concept Typed = requires(Buf buf) {
  { mpi::type(buf) } -> std::same_as<MPI_Datatype>;
};
```

```
template <typename T>
concept DataBuffer =
  std::ranges::contiguous_range<T> &&
  std::ranges::sized_range<T> && mpi::Typed<T>;

template <typename T>
concept SendBuffer =
  DataBuffer<T> &&
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template <typename T>
concept RecvBuffer =
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template<SendBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
  return MPI_Sendrecv(std::ranges::data(s), std::ranges::size(s), mpi::type(s), dest, ...);
}
```

Problem: ad-hoc, limited to a fixed set of containers → **Solution:** define general concepts

```
template <typename Buf>
concept Typed = requires(Buf buf) {
  { mpi::type(buf) } -> std::same_as<MPI_Datatype>;
};

template <typename Buf>
  requires mpi::has_static_type<
             std::ranges::range_value_t<Buf>> ||
           has_type_member<Buf>
MPI_Datatype type(Buf &buf) {
  if constexpr (has_type_member<Buf>) {
    return buf.type();
  } else {
    type_traits<std::ranges::range_value_t<Buf>>();
  }
}
```

```
template <typename T>
concept DataBuffer =
  std::ranges::contiguous_range<T> &&
  std::ranges::sized_range<T> && mpi::Typed<T>;

template <typename T>
concept SendBuffer =
  DataBuffer<T> &&
  std::ranges::input_range<T>;

template <typename T>
concept RecvBuffer =
  DataBuffer<T> &&
  std::ranges::output_range<T,
      std::ranges::range_value_t<T>>;
```

Modeling Data

Handling Memory Buffers

```
template<SendBuffer SendBuf>
int sendrecv(SendBuf&& s, int dest, ...) {
  return MPI_Sendrecv(std::ranges::data(s), std::r
}
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// send a kokkos view, internally repacking data
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Modeling Data

Handling Memory Buffers

```
template<SendBuffer SendBuf>
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```

Collectives with varying counts

```
std::vector<int> send_buf = {...};
std::vector<int> recv_buf = {...};

// does not compile, send_buf
// needs members .sizev() and .displs()
comm.scatterv(send_buf, recv_buf, root);

// adapt data buffer with count information
comm.scatterv(
  mpi::vbuf {send_buf, scounts, sdisp},
  recv_buf,
  root
);
```

```
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Modeling Data

Ownership

- Modeling data as **data buffers** allows for a better **ownership** model
- Clear **responsibility** for freeing memory

```
std::vector<int> recv_buf = {...};

recv_buf = comm.recv(std::move(recv_buf), ...);
```

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```
std::vector<int> recv_buf = {...};
                   transfer ownership to library

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captured by reference
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auto req = comm.irecv(          recv_buf , ...);

// ... other computations

                  req.wait(...);
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Modeling Data

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return ownership to caller

```cpp
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```cpp
std::optional<std::vector<int>> result = req.test(...);
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Handling Errors

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Errors via exceptions

```
try {
  std::vector<int> buf = comm.recv(std::vector<int>(recv_size), src, tag);
  // [...] computation
} catch (const mpi::exception& e) {
  std::cerr << "Recv failed: " << e.what() << "\n";
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Errors via `std::expected`

```
std::expected result = comm.recv(std::vector<int>(recv_size), src, tag);
if (result) {
  std::vector buf = std::move(*result);
  // [...] computation
} else {
  std::cerr << "Recv␣failed:␣"
            << result.error().message() << "\n";
  auto recovered_buffer = std::move(result).error().recv_buf();
}
```

Conclusion

We started deriving **language support guidelines** for C++

Core aspects

- Object model
- Data representation
- Ownership
- Modeling and mapping types
- Idiomatic error handling

Future work

- Build a reference implementation (+ extensions for accelerators, libraries, . . .)
- Concretize guidelines for non-blocking, one-sided, partitioned, . . . communication
- Improve MPI's language interoperability, without sacrificing a C++ performance path

Open Question: How to bring C++ back to the MPI standard?

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Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 882500).

PSAAP Funding in part is acknowledged from these NSF Grants OAC-2514054, CNS-2450093, CCF-2405142, and CCF-2412182 and the U.S. Department of Energy's National Nuclear Security Administration (NNSA) under the Predictive Science Academic Alliance Program (PSAAP-III), Award DE-NA0003966.

AAC work performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, and supported by the Center for Non-Perturbative Studies of Functional Materials Under Non-Equilibrium Conditions (NPNEQ) funded by the Computational Materials Sciences Program of the US Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. This work was also performed under the auspices of the US Department of Energy's Pacific Northwest National Laboratory, operated by Battelle Memorial Institute under contract DE-AC05-76RL01830.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation, or the U.S. Department of Energy's National Nuclear Security Administration.