Making code thread-safe

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- What language are you using?
  – Multi-threading in (e.g.) C++ is harder
  – Multi-threading in (e.g.) Go, Rust, Haskell is easier

- Are you starting from scratch or retrofitting code?

- Does it make sense for the code in question to be multi-threaded?

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- What language are you using?
  - Multi-threading in (e.g.) C++ is harder
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- Are you starting from scratch or retrofitting code?

- Does it make sense for the code in question to be multi-threaded?

> When writing multi-threaded code, you should always ask:
>
> ***What's the context in which this function will be called?***

Thread-safety matrix

Thread-safety matrix

Is the object shared across threads?

Yes	No

Thread-safety matrix

Is the object mutable? / Is the object shared across threads?	Yes	No
Yes		
No		

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Thread-safety matrix

Is the object shared across threads?

Is the object mutable?	Yes	No
Yes	Data races possible	OK
No	OK	OK

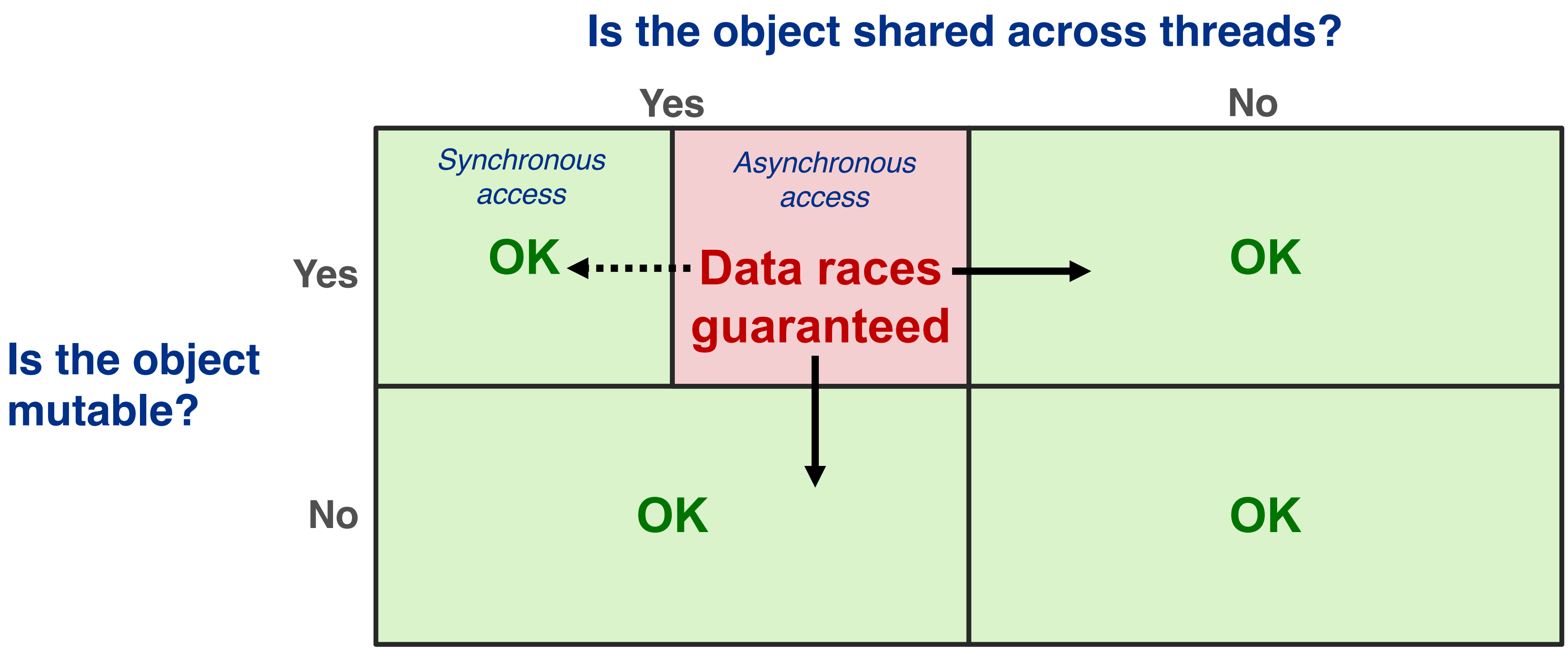
Thread-safety matrix

Is the object shared across threads?

Is the object mutable?

Is the object mutable?	Yes		No
	Synchronous access	*Asynchronous access*	
Yes	**OK**	**Data races guaranteed**	**OK**
No	**OK**		**OK**

Thread-safety matrix



You must get out of that box!

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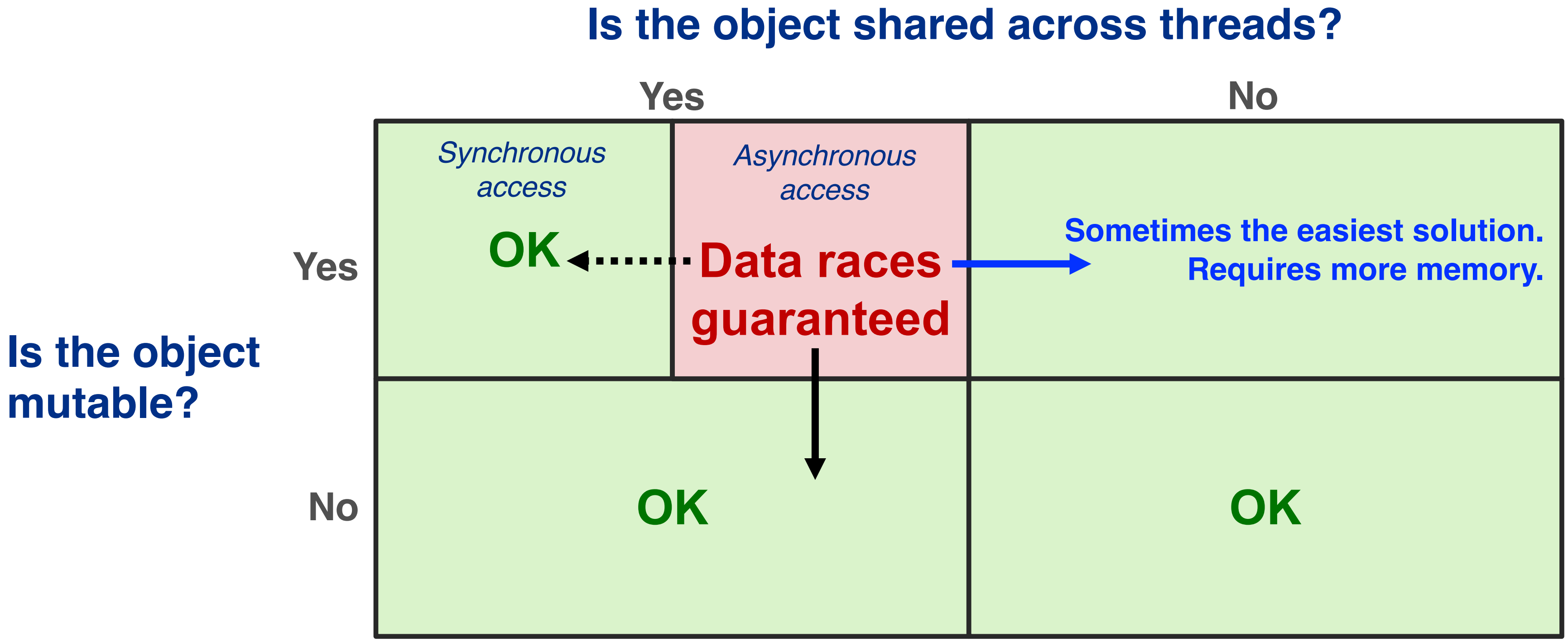
Thread-safety matrix



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Thread-safety matrix

Is the object shared across threads?

Is the object mutable?

Is the object mutable?	Yes: *Synchronous access*	Yes: *Asynchronous access*	No
Yes	**OK**	**Data races guaranteed**	Sometimes the easiest solution. Requires more memory.
No	Memory savings. Can be difficult to make things immutable.		**OK**

Thread-safety matrix

Is the object shared across threads?

Is the object mutable?

	Yes		No
Yes	*Synchronous access* ***Awkward.*** **Will not discuss.**	*Asynchronous access* **Data races guaranteed**	**Sometimes the easiest solution. Requires more memory.**
No	**Memory savings. Can be difficult to make things immutable.**		**OK**

Thread-safety matrix

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Is the object shared across threads?</td></tr>
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Can be difficult to make things immutable.</td><td>OK</td></tr>
</table>

Making your code thread-safe often requires a combination of methods.

To make your code thread-safe…

- ***You must know what is shared among threads, and the contexts in which the sharing happens.***

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- ***You must know what is shared among threads, and the contexts in which the sharing happens.***

- **Game – Part 1**
  - Thread-safety and free-functions

- **Game – Part 2**
  - Thread-safety and class member functions

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Part 1: Is it thread-safe?

The pattern we'll follow

```
void test(...)
{
  // ...
}

int main()
{
  execute_with_10_threads(test, ...);
}
```

Part 1: Is it thread-safe?

```
void test()
{}

int main()
{
  execute_with_10_threads(test);
}
```

Part 1: Is it thread-safe?

```
void test()
{}

int main()
{
  execute_with_10_threads(test);
}
```

Yes

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Part 1: Is it thread-safe?

```
void test()
{
  auto i = 42;
}

int main()
{
  execute_with_10_threads(test);
}
```

Part 1: Is it thread-safe?

```
void test()
{
  auto i = 42;
}

int main()
{
  execute_with_10_threads(test);
}
```

Yes

Each thread gets its own stack memory.

Part 1: Is it thread-safe?

```
void test(int j)
{
  ++j;
}

int main()
{
  auto i = 42;
  execute_with_10_threads(test, i);
}
```

Part 1: Is it thread-safe?

```
void test(int j)
{
  ++j;
}

int main()
{
  auto i = 42;
  execute_with_10_threads(test, i);
}
```

Yes

The value 42 is copied into j for each thread.

Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  ++j;
}

int main()
{
  execute_with_10_threads(test);
}
```

Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  ++j;
}

int main()
{
  execute_with_10_threads(test);
}
```

No

j is shared across all threads that call test

`operator++` requires a read and then write

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Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  int k = j;
  ++k;
}

int main()
{
  execute_with_10_threads(test);
}
```


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Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  int k = j;
  ++k;
}

int main()
{
  execute_with_10_threads(test);
}
```

Yes

Although j is shared, its value never changes
k is a stack variable.

This is fragile, though!

Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  int& k = j;
  ++k;
}

int main()
{
  execute_with_10_threads(test);
}
```


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Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  int& k = j;
  ++k;
}

int main()
{
  execute_with_10_threads(test);
}
```

No

k now refers to a shared object!

`operator++` requires a read and then write

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Part 1: Is it thread-safe?

```
void test()
{
  static int j{0};
  int& k = j;
  ++k;
}

int main()
{
  execute_with_10_threads(test);
}
```

One character can break a program.

No

ow refers to
ared object!

`operator++` requires
a read and then write

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Part 1: Is it thread-safe?

```cpp
void test(std::string const& sentence)
{
  auto pos = sentence.find("C++17");
}

int main()
{
  std::string sentence{"I love C++17."};
  execute_with_10_threads(test, sentence);
}
```

Part 1: Is it thread-safe?

```
void test(std::string const& sentence)
{
  auto pos = sentence.find("C++17");
}

int main()
{
  std::string sentence{"I love C++17."};
  execute_with_10_threads(test, sentence);
}
```

Yes

In general, calling const-qualified C++ STL member functions is thread-safe…

assuming another thread isn't adjusting the object.

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Part 1: Is it thread-safe?

```
void test()
{
  MyArbitraryType t;
}

int main()
{
  execute_with_10_threads(test);
}
```

Part 1: Is it thread-safe?

```
void test()
{
  MyArbitraryType t;
}

int main()
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  execute_with_10_threads(test);
}
```

It depends

Part 1: Is it thread-safe?

```cpp
void test()
{
  MyArbitraryType t;
}

int main()
{
  execute_with_10_threads(test);
}
```

```cpp
using MyArbitraryType = int;
```

Part 1: Is it thread-safe?

```
void test()
{
  MyArbitraryType t;
}

int main()
{
  execute_with_10_threads(test);
}
```

```
using MyArbitraryType = int;
```

Yes

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Part 1: Is it thread-safe?

```
void test()
{
  MyArbitraryType t;
}

int main()
{
  execute_with_10_threads(test);
}
```

```
struct MyArbitraryType {
  MyArbitraryType()
  {
    static int counter;
    ++counter;
  }
};
```


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Part 1: Is it thread-safe?

```
void test()
{
  MyArbitraryType t;
}

int main()
{
  execute_with_10_threads(test);
}
```

```
struct MyArbitraryType {
  MyArbitraryType()
  {
    static int counter;
    ++counter;
  }
};
```

No

Although there is one 't' per thread, the constructor accesses shared memory.

Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test(...)
  {
    // ...
  }
};

int main()
{
  MyClass obj;
  execute_with_10_threads(&MyClass::test, obj, ...);
}
```

The pattern we'll follow

Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test()
  {}
};

int main()
{
  MyClass obj;
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}
```

Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test()
  {}
};

int main()
{
  MyClass obj;
  execute_with_10_threads(&MyClass::test, obj);
}
```

Yes

Part 2: Is it thread-safe?

```
class MyClass {
  int count_{0};

public:
  void test()
  {
    ++count_;
  }
};

int main()
{
  MyClass obj;
  execute_with_10_threads(&MyClass::test, obj);
}
```

Part 2: Is it thread-safe?

```
class MyClass {
  int count_{0};

public:
  void test()
  {
    ++count_;
  }
};

int main()
{
  MyClass obj;
  execute_with_10_threads(&MyClass::test, obj);
}
```

No

The class data for obj (count_) is shared across threads.

`operator++` requires a read and then write

Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test(MyOtherClass& oc)
  {
    auto const h = oc.getSomething();
  }
};

int main()
{
  MyClass obj;
  MyOtherClass oc;
  execute_with_10_threads(&MyClass::test, obj, oc);
}
```


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Part 2: Is it thread-safe?

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class MyClass {
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It depends

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Part 2: Is it thread-safe?

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  }
};

int main()
{
  MyClass obj;
  MyOtherClass oc;
  execute_with_10_threads(&MyClass::test, obj, oc);
}
```

```
class MyOtherClass {
public:
  int getSomething() const
  {
    return 42;
  }
};
```

Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test(MyOtherClass& oc)
  {
    auto const h = oc.getSomething();
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int main()
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  execute_with_10_threads(&MyClass::test, obj, oc);
}
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class MyOtherClass {
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Yes

Part 2: Is it thread-safe?

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};

int main()
{
  MyClass obj;
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  execute_with_10_threads(&MyClass::test, obj, oc);
}
```

```
class MyOtherClass {
public:
  int getSomething() const
  {
    static int i{42};
    ++i;
    return i;
  }
};
```


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Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test(MyOtherClass& oc)
  {
    auto const h = oc.getSomething();
  }
};

int main()
{
  MyClass obj;
  MyOtherClass oc;
  execute_with_10_threads(&MyClass::test, obj, oc);
}
```

```
class MyOtherClass {
public:
  int getSomething() const
  {
    static int i{42};
    ++i;
    return i;
  }
};
```

No!

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Part 2: Is it thread-safe?

```
class MyClass {
public:
  void test(MyOtherClass& oc)
  {
    auto const h = oc.getSomething();
  }
};

int main()
{
  MyClass obj;
  MyOtherClass oc;
  execute_with_10_threads(&MyClass::test, obj, oc);
}
```


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Part 2: Is it thread-safe?

```
class MyClass {
public:
  void produce(art::Event& e)
  {
    auto const h = e.getValidHandle();
  }
};

int main()
{
  MyClass obj;
  art::Event e;
  execute_with_10_threads(&MyClass::produce, obj, e);
}
```

Determining thread-safety …

- Takes analysis!

- Know what objects are shared.

- Know when they are shared.

Considerations for *art*

- Who owns your module?

Considerations for *art*

- Who owns your module?

- *art* owns the module objects, which are created at run-time based on the configuration you provide.

- You provide the *definition* of the module class:
  - *art* knows very little of your module's definition
  - ***art*** calls module functions via C++ polymorphism

- Suppose *art* were to call your `produce` function concurrently on multiple events.

Module example

- We want to create a track from a collection of hits

```
void TrackMaker::produce(art::Event& e)
{
  auto const& hits = e.getValidHandle<Hits>(tag_);
  unique_ptr<Track> track = trackFromHits(*hits);
  e.put(move(track));
}
```

Module example

- We want to create a track from a collection of hits

```
void TrackMaker::produce(art::Event& e)
{
  auto const& hits = e.getValidHandle<Hits>(tag_);
  unique_ptr<Track> track = trackFromHits(*hits);
  e.put(move(track));
}
```

- Assuming `trackFromHits` does not update any state, then this `produce` function is thread-safe—i.e. it can be called concurrently with different `art::Event` objects.
- Why?
  - *art* guarantees that product retrieval and insertion is thread-safe
  - the produce function above modifies no state of the TrackMaker object

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Indications of thread-*unsafe* C++ code

- Functions (free or member) which access a global object whose state can change, including non-`const` function-scope `static` data.
- Functions (free or member) which change the state of objects which were passed as `const` function arguments (e.g. casting away `const` on an argument).
- `const` non-`static` member functions which modify the state of the object on which they are called (e.g. `mutable` members, or casting away `const` on this).
- Pointer member data or data held by member data being passed as a non-`const` argument to functions.
- `const` member functions returning values of member variables which are pointers to non-`const` items.

General guidelines

- Apply `const` liberally
- Avoid using non-`const` `static` variables in functions/classes
- To the extent possible, do not use the `mutable` keyword
- Use as few global objects as possible
- If you must use a global object, provide only `const`-qualified interface
- Don't use output arguments

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Discouraged

```
void fillInts(std::vector<int>& ints)
{
  for (size_t i{0}; i < 42; ++i)
    ints.push_back(some_calculation(i));
}
std::vector<int> ints;
fillInts(ints);
```

Encouraged

```
auto getInts()
{
  std::vector<int> ints;
  for (size_t i{0}; i < 42; ++i)
    ints.push_back(some_calculation(i));
  return ints;
}
auto const ints = getInts();
```

General guidelines

- Apply `const` liberally
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- Use as few global objects as possible
- If you must use a global object, provide only `const`-qualified interface
- Don't use output arguments

All of these are good ideas for single-threaded code.
You can do this now!