No Littering!

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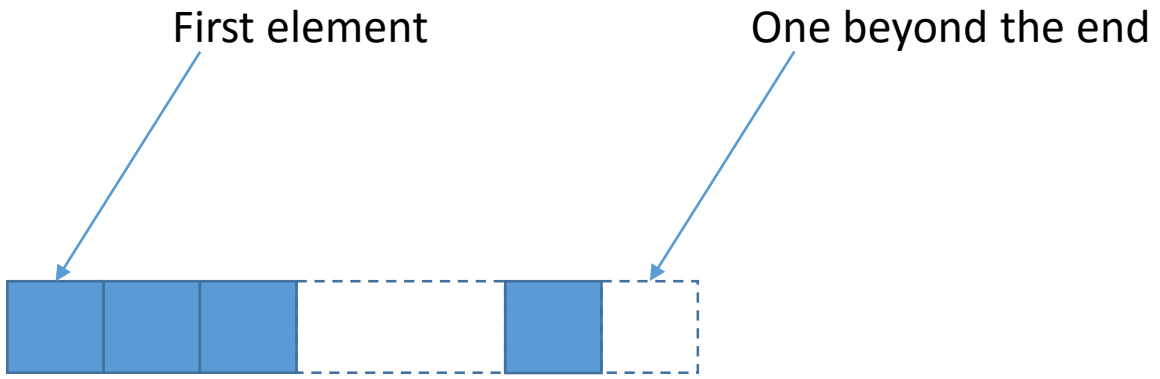
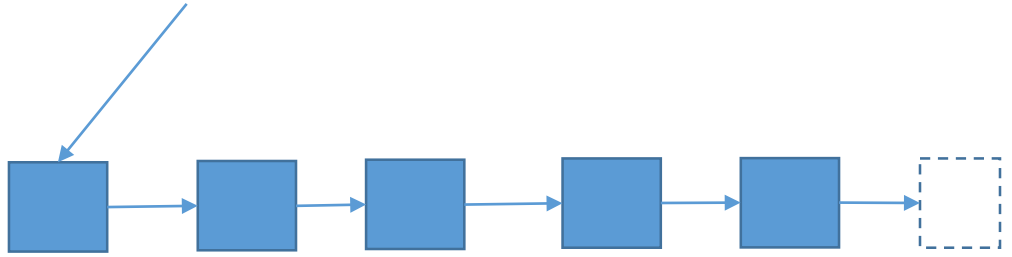
Something else

- Concepts
  - Look at Andrew Sutton's talks and writings (e.g., Overload) (Approved TS)
  - Look at Eric Niebler's: Ranges (new TS)
- Concurrency
  - J. Daniel Garcia and B. Stroustrup: Improving performance and maintainability through refactoring in C++11. To be presented at ACCU in Bristol
- Coroutines
  - Look at Gor Nisharov's writings and talks
  - Come to the SFBay-ACCU event tomorrow: Sumant Tambe
- There is so much going on!
  - Isocpp.org
  - Cppcon videos
  - …

I like pointers!

- Pointers are what the hardware offers
  - Machine addresses
  - For good reasons
    - They are simple
    - They are general
    - They are fast
    - They are compact
- "offsets" are simply kinds of local pointers
- C's memory model has served us really well
  - Sequences of objects
- But pointers are not "respectable"
  - dangerous, low-level, not mathematical, …
  - There is a huge ABP crowd



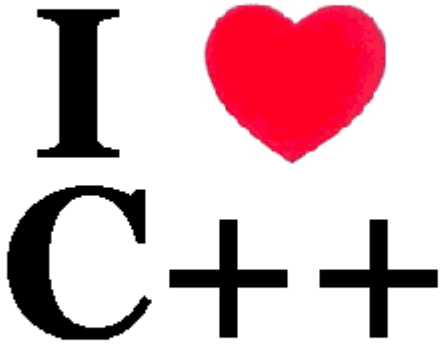


Overview

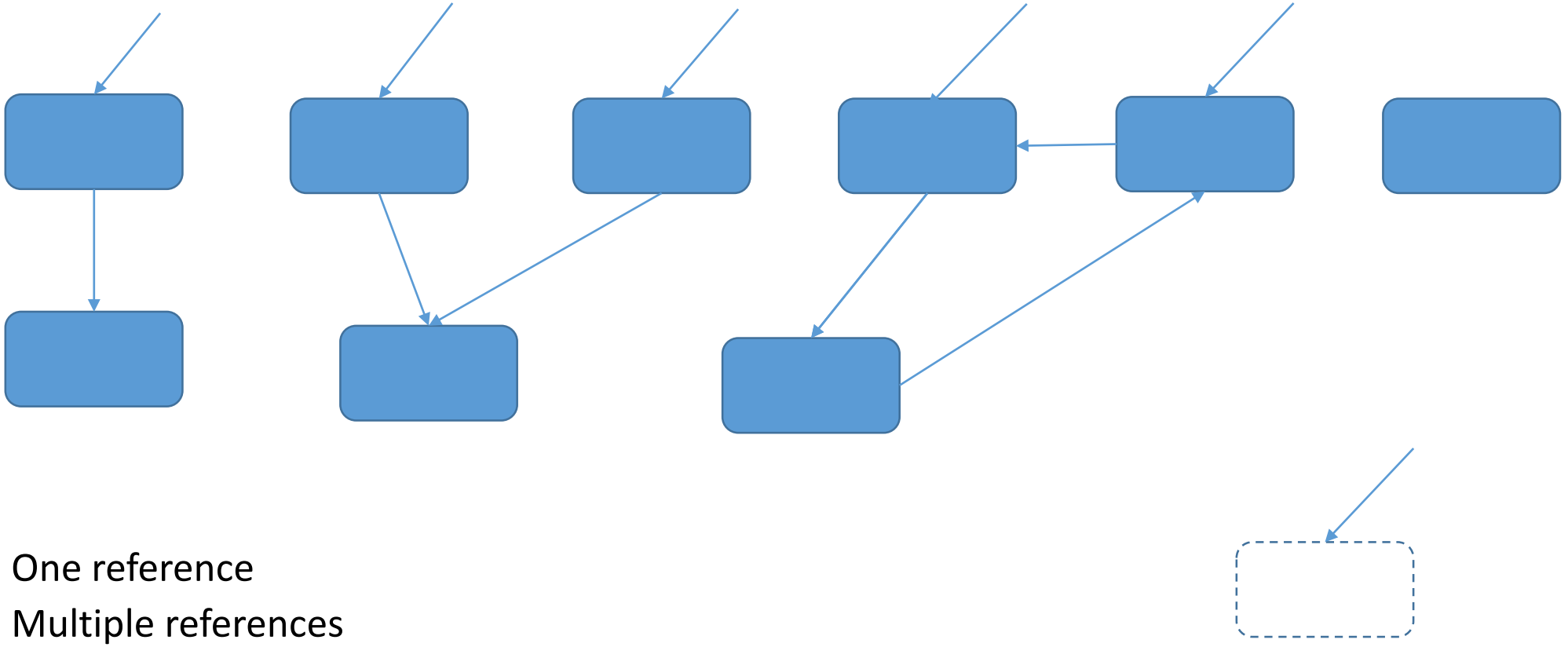
- Pointer problems
  - Memory corruption
  - Resource leaks
  - Expensive run-time support
  - Complicated code
- The solution
  - Eliminate dangling pointers
  - Eliminate resource leaks
  - Library support for range checking and nullptr checking

Executive summary

- We now offer complete type- and resource-safety
  - Guaranteed
  - No litter
  - No resource leaks
  - No garbage collector (because there is no garbage to collect)
  - No runtime overheads
    - Except necessary range checks
  - Simpler code
- Part of a more ambitious project (C++ Core Guidelines")
  - https://github.com/isocpp/CppCoreGuidelines
- We want "C++ on steroids"
  - Not some neutered subset

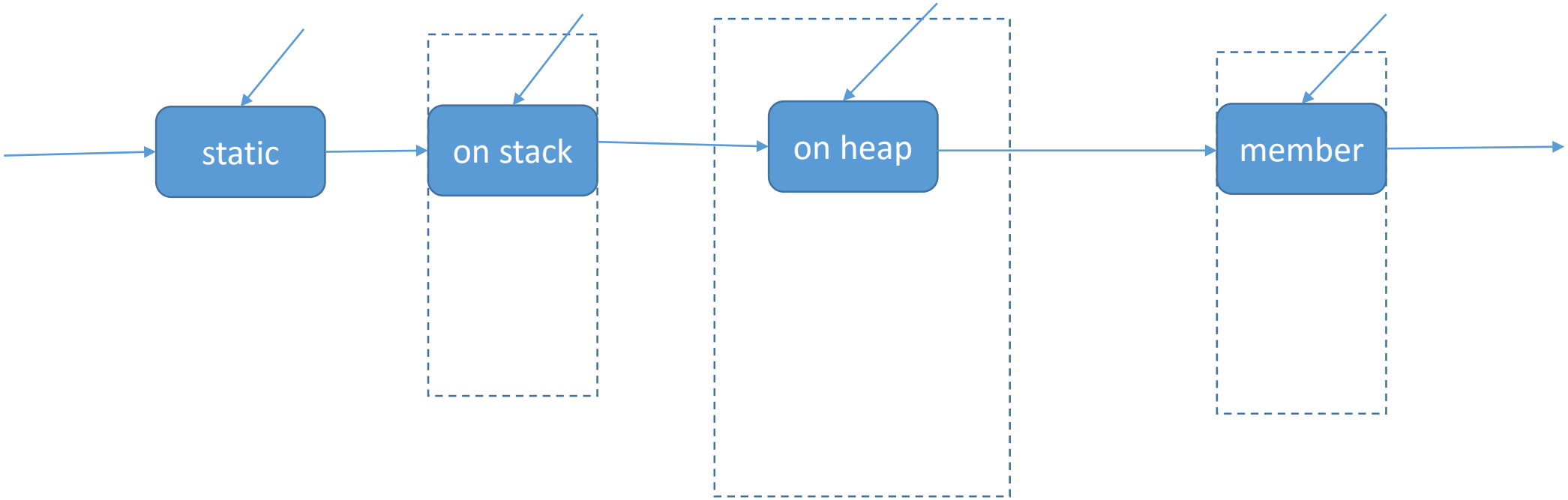


Lifetime can be messy



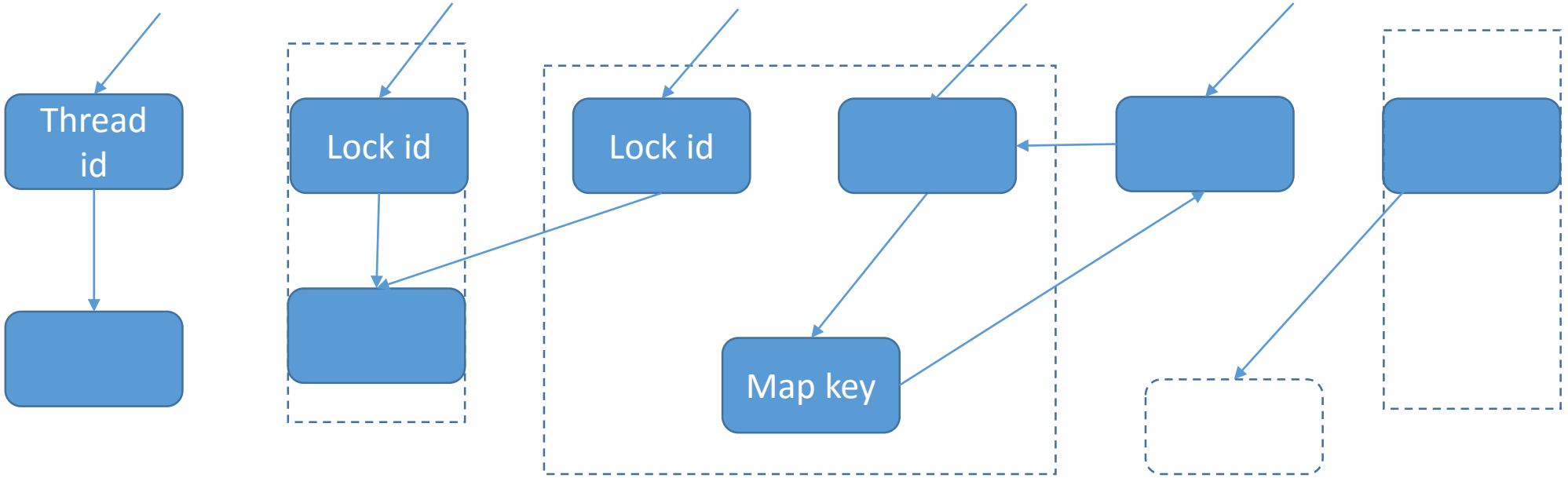
- One reference
- Multiple references
- Loops
- No references (leak)
- Reference after deletion (dangling pointer)

Ownership can be messy



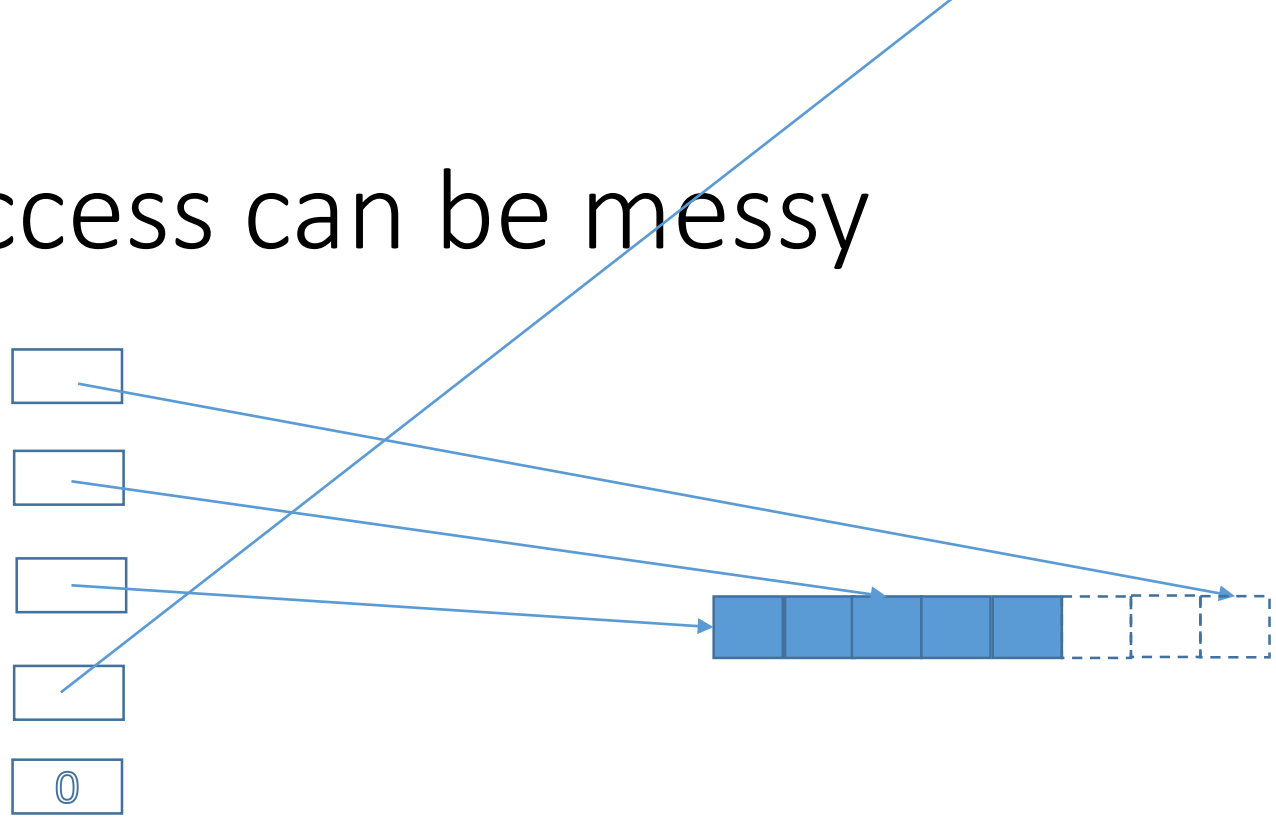
- Object on stack (automatically freed)
- Object on free store (must be freed)
- Object in static store (must never be freed)
- Object in other object

Resource management can be messy



- Objects are not just memory
- Semantically interesting cleanup is sometimes needed
  - File handles
  - Thread handles
  - Locks
  - …

Access can be messy



- Problems:
  - Range error
  - **nullptr** dereference
  - Unititialized pointer
  - **const** violation

No littering, no leaks, no corruption

- Every object is constructed before use
  - Once only
  - initialized
- Every fully constructed object is destroyed
  - Once only
  - In particular
    - Every object allocated on the free store must be **delete**d
    - No object not allocated on the free store must be **delete**d
- No access through a pointer that is not pointing to an object
  - Read or write
  - Off the end of an object (out of range)
  - To **delete**d object
  - To “random” place in memory (e.g., uninitialized pointer)
  - Through **nullptr** (originally: “there is no object at address zero”)

Current (Partial) Solutions

- Ban or seriously restrict pointers
  - Add indirections everywhere
  - Add checking everywhere
- Manual memory management
  - Possible combined with manual non-memory resource management
- Garbage collectors
  - Plus manual non-memory resource management
- Static analysis
  - To supplement manual memory management
- “Smart” pointers
  - Starting with counted pointers
- Functional Programming
  - Eliminate pointers

Current (Partial) Solutions

- These are old problems and old solutions
  - 40+ years
- Manual resource management doesn't scale
- Smart pointers add complexity and cost
- Garbage collection is at best a partial solution
  - Doesn't handle non-memory solutions ("finalizers are evil")
  - Is expensive
  - Is non-local (systems are often distributed)
  - Introduces non-predictability
- Static analysis doesn't scale
  - False positives
  - Dynamic linking and other dynamic phenomena

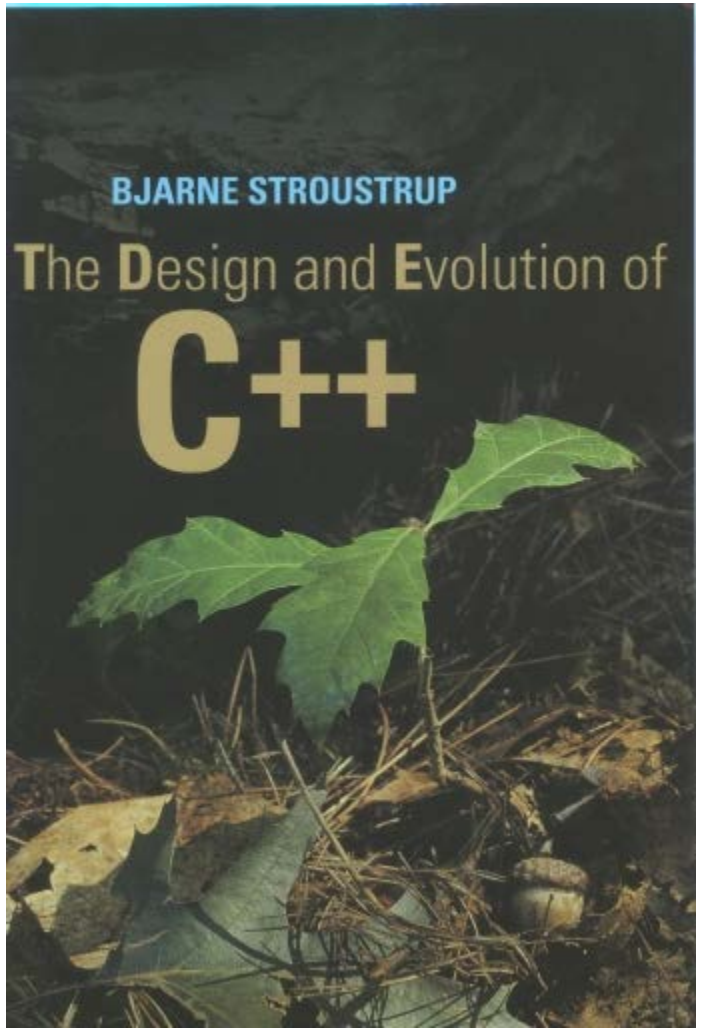
A solution

- Be precise about ownership
  - Don’t litter
  - Static guarantee
- Eliminate dangling pointers
  - Static guarantee
- Make general resource management implicit
  - Hide every explicit delete/destroy/close/release
- Test for **nullptr** and range
  - Do minimal run-time checking

- There are other problems with C++ pointers
  - Dealt with by other rules

Constraints on the solution

- I want it ***now***
  - I don't want to invent a new language
  - I don't want to wait for a new standard
- I want it guaranteed
  - Not just "do it this way and be careful"
- Don't sacrifice
  - Generality
  - Performance
  - Simplicity
  - Portability
- Part of C++ Core Coding guidelines
  - Supported by a "guidelines support library" (GSL)
  - Supported by analysis tools



No resource leaks

- We know how
  - Root every object in a scope
    - **vector<T>**
    - **string**
    - **ifstream**
    - **unique_ptr<T>**
    - **shared_ptr<T>**
  - RAII
    - "No naked **new**"
    - "No naked **delete**"
  - Constructor/destructor
    - "since 1979, and still the best"

Dangling pointers – the worst problem

- One nasty variant of the problem

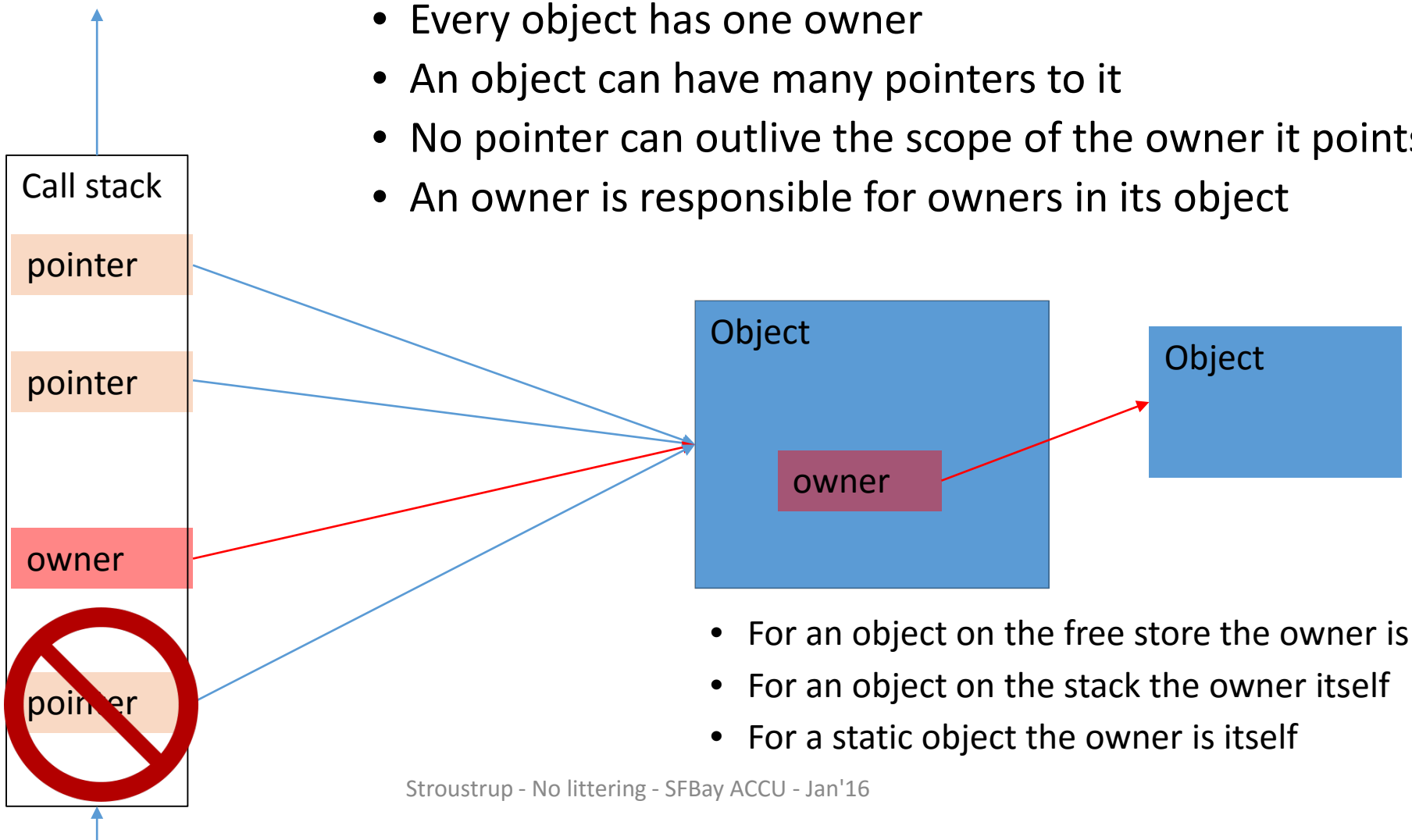
```
void f(X* p)
{
        // …
        delete p;           // looks innocent enough
}

void g()
{
        X* q = new X;       // looks innocent enough
        f(q);
        // … do a lot of work here …
        q->use();           // Ouch! Read/scramble random memory
}
```

Dangling pointers

- We ***must*** eliminate dangling pointers
  - Or type safety is compromised
  - Or memory safety is compromised
  - Or resource safety is compromised
- Eliminated by a combination of rules
  - Distinguish owners from non-owners
  - Assume raw pointers to be non-owners
  - Catch all attempts for a pointer to “escape” into a scope enclosing its owner’s scope
    - **return**, **throw**, out-parameters, long-lived containers, …
  - Something that holds an owner is an owner
    - E.g. **vector<owner<int*>>**, **owner<int*>[]**, …

Owners and pointers



- Every object has one owner
- An object can have many pointers to it
- No pointer can outlive the scope of the owner it points to
- An owner is responsible for owners in its object

- For an object on the free store the owner is a pointer
- For an object on the stack the owner itself
- For a static object the owner is itself

Dangling pointers

- Ensure that no pointer outlives the object it points to

```
void f(X* p)
{
        // …
        delete p;               // bad: delete non-owner
}

void g()
{
        X* q = new X;           // bad: assign object to non-owner
        f(q);
        // … do a lot of work here …
        q->use();               // Make sure we never get here
}
```

How do we represent ownership?

- High-level: Use an ownership abstraction
  - This is simple and preferred
- Low-level: mark owning pointers **owner**
  - An **owner** must be **delete**d or passed to another **owner**
  - A non-**owner** may not be **delete**d
  - This is essential in places but does not scale

- What I say applies to anything that refers to an object
  - Pointers
  - References
  - Containers of pointers
  - Smart pointers
  - …

How do we represent ownership?

- Mark an owning **T***: **owner<T*>**
  - Initial idea
    - Yet another kind of “smart pointer”
    - **owner<T*>** would hold a **T*** and an “owner bit”
    - Costly: bit manipulation
    - Not ABI compatible
    - Not C compatible
  - So our GSL **owner** is
    - A handle for static analysis
    - Documentation
    - Not a type with it’s own operations
    - Cost free: No run-time cost (time or space)
    - ABI compatible
    - **template<typename T> using owner = T;**

GSL: owner<T>

- How do we implement ownership abstractions?

```
template<SemiRegular T>
class vector {
public:
        // …
private:
        owner<T*> elem;          // the anchors the allocated memory
        T* space;                // just a position indicator
        T* end;                  // just a position indicator
        // …
};
```

- **owner<T*>** is just an alias for **T***

GSL: owner<T>

- How about code we cannot change?
  - ABI stability

```
void foo(owner<int*>);          // foo requires an owner

void f(owner<int*> p, int* q, owner<int*> p2, int* q2)
{
    foo(p);                     // OK: transfer ownership
    foo(q);                     // bad: q is not an owner
    delete p2;                  // necessary
    delete q2;                  // bad: not an owner
}
```

- A static analysis tool can tell us where our code mishandles ownership

owner is a low-level mechanism

- Use proper ownership abstractions
  - E.g., **unique_ptr** and **vector**
    - Implemented using **owner**
- **owner** is intended to simplify static analysis
  - **owner**s in application code is a sign of a problem
    - Usually, C-style interfaces
  - "Lots of annotations" doesn't scale
    - Becomes a source of errors

A cocktail of techniques

- Not a single neat miracle cure
  - Rules (from the “Core C++ Guidelines)
    - Statically enforced
  - Libraries (STL, GSL)
    - So that we don’t have to directly use the messy parts of C++
  - Reliance on the type system
    - The compiler is your friend
  - Static analysis
    - Essentially to extend the type system

- Each of those techniques are insufficient by itself
- Not just for C++
  - But the “cocktail” relies on much of C++

How to avoid/catch dangling pointers

- Rules (giving pointer safety):
  - Don’t transfer to pointer to a local to where it could be accessed by a caller
  - A pointer passed as an argument can be passed back as a result
  - A pointer obtained from new can be passed back as a result as an owner

```
int*  f(int* p)
{
        int x = 4;
        return &x;                  // No! would point to destroyed stack frame
        return new int{7};          // OK (sort of): doesn’t dangle, should return an owner<int*>
        return p;                   // OK: came from caller
}
```

How to avoid/catch dangling pointers

- Classify pointers according to ownership

```
vector<int*> f(int* p)
{
        int x = 4;
        owner<int*> q = new int{7};
        vector<int*> res = {p, &x, q};          // Bad: { unknown, pointer to local, owner }
        return res;
}
```

- Here
  - Don’t mix different ownerships in an array
  - Don’t let different return statements of a function mix ownership

Dangling pointer summary

- Simple:
  - We never let a “pointer” point to an out-of-scope object
- It’s not just pointers
  - All ways of “escaping”
    - **return**, **throw**, place in long-lived container, …
  - Same for containers of pointers
    - E.g. **vector<int*>**, **unique_ptr<int>**, iterators, built-in arrays, …
  - Same for references
- Concurrency
  - Keep threads alive with scoping or shared_ptr
  - Apply the usual rules for a thread’s stack
  - Threat another thread as just another object (it is).

Other problems

- Other ways of breaking the type system
  - Unions: use variant
  - Casts: don't use them
  - …
- Other ways of misusing pointers
  - Range errors: use **span<T>**
  - **nullptr** dereferencing: use **not_null<T>**
- Wasteful ways of addressing pointer problems
  - Misuse of smart pointers
- …
- "Just test everywhere at run time" is ***not*** an acceptable answer
  - We want comprehensive guidelines

GSL – span<T>

- Common interface style
  - major source of bugs

```
void f(int* p, int n)              // what is n? (How would a tool know?)
{
        p[7] = 9;                                  // OK?
        for (int i=0; i<n; ++i) p[i] = 7;          // OK?
}
```

- Better

```
void f(span<int> a)
{
        a[7] = 9;                                  // OK? Checkable against a.size()
        for (int& x : a) x = 7;                    // OK
}
```

GSL – span<T>

- Common style

```
void f(int* p, int n);
int a[100];
// …
f(a,100);
f(a,1000);     // likely disaster
```

- Better

```
void f(span<int> a)
int a[100];
// …
f(span<int>{a});
f(a);
f({a,1000});   // easily checkable
```

- “Make simple things simple”
  - Simpler than “old style”
  - Shorter
  - At least as fast

nullptr problems

- Mixing **nullptr** and pointers to objects
  - Causes confusion
  - Requires (systematic) checking
- Caller

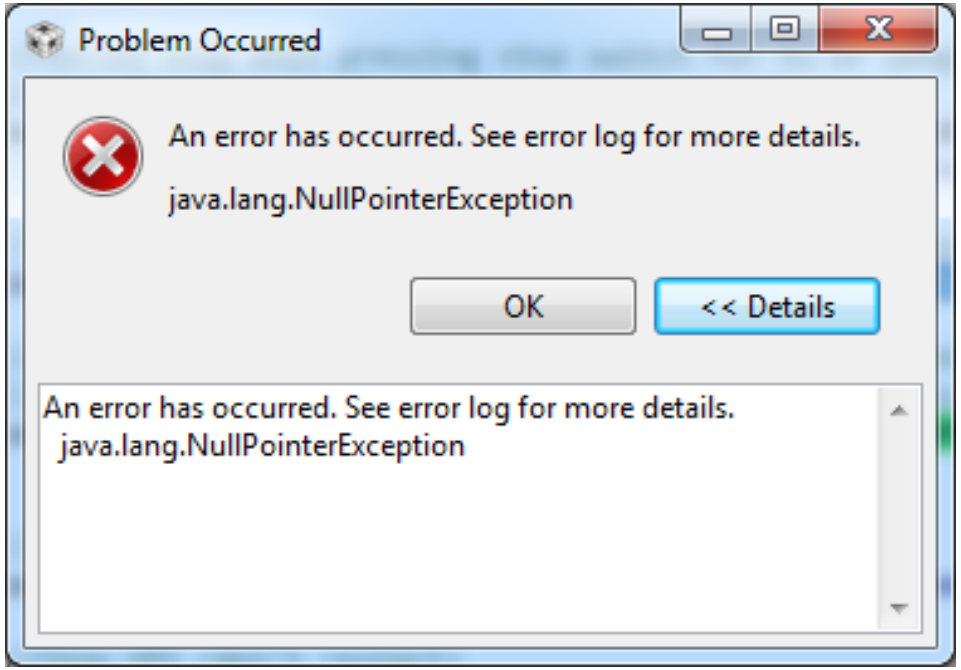
```
void f(char*);

f(nullptr);              // OK?
```

- Implementer

```
void f(char* p)
{
        if (p==nullptr)      // necessary?
        // …
}
```

- Can you trust the documentation?
- Compilers don't read manuals, or comments
- Complexity, errors, and/or run-time cost



GSL – not_null<T>

- Caller

```
void f(not_null<char*>);

f(nullptr);     // Obvious error: caught be static analysis
char* p = nullptr;
f(p);           // Constructor for not_null can catch the error
```

- Implementer

```
void f(not_null<char*> p)
{
    // if (p==nullptr) // not necessary
    // …
}
```

GSL – not_null<T>

- **not_null<T>**
  - A simple, small class
    - Should it be an alias like **owner**?
  - **not_null<T*>** is **T*** except that it cannot hold **nullptr**
  - Can be used as input to analyzers
    - Minimize run-time checking
  - Checking can be “debug only”
  - For any **T** that can be compared to **nullptr**

To summarize

- Type and resource safety:
  - RAII (scoped objects with constructors and destructors)
  - No dangling pointers
  - No leaks (track ownership pointers)
  - Eliminate range errors
  - Eliminate nullptr dereference
- That done, we attack other sources of problems
  - Logic errors
  - Performance bugs
  - Maintenance hazards
  - Verbosity
  - …

Current state: the game is changing dramatically

- Papers
  - B. Stroustrup, H. Sutter, G. Dos Reis: A brief introduction to C++'s model for type- and resource-safety.
  - H. Sutter and N. MacIntosh: Preventing Leaks and Dangling
  - T. Ramananandro, G. Dos Reis, X Leroy: A Mechanized Semantics for C++ Object Construction and Destruction, with Applications to Resource Management
- Code
  - https://github.com/isocpp/CppCoreGuidelines
  - https://github.com/microsoft/gsl
  - Static analysis: coming soon (Microsoft: January or February)
- Videos
  - B. Stroustrup: : Writing Good C++ 14
  - H. Sutter: Writing good C++ 14 By Default
  - G. Dos Reis: Contracts for Dependable C++
  - N. MacIntosh: Static analysis and C++: more than lint
  - N. MacIntosh: A few good types: Evolving array_view and string_view for safe C++ code

(Mis)uses of smart pointers

- "Smart pointers" are popular
  - To represent ownership
  - To avoid dangling pointers
- "Smart pointers" are overused
  - Can be expensive
    - E.g., **shared_ptr**
  - Can mess up interfaces fore otherwise simple functions
    - E.g. **unique_ptr** and **shared_ptr**
  - Often, we don't need a pointer
    - Scoped objects
    - We need pointers
      - For OO interfaces
      - When we need to change the object referred to

But ordinary pointers don't dangle any more

(Mis)uses of smart pointers

- Consider
  - **void f(T*);** // *use; no ownership transfer or sharing*
  - **void f(unique_ptr<T>);** // *transfer unique ownership and use (uncommon style)*
  - **void f(shared_ptr<T*>);** // *share ownership and use (implies cost)*
- Taking a raw pointer (**T***)
  - Is familiar
  - Is simple, general, and common
  - Is cheaper than passing a smart pointer (usually)
  - Doesn't lead to dangling pointers (now!)
  - Doesn't lead to replicated versions of a function for different shared pointers
- In terms of tradeoffs with smart pointers, other simple "object designators" are equivalent to **T***
  - iterators, references, **span**, etc.

Rules, standards, and libraries

- Could the rules be enforced by the compiler?
  - Some could, but we want to use the rules ***now***
    - Some compiler support would be very nice; let's talk
  - Many could not
  - Rules will change over time
  - Compilers have to be more careful about false positives
  - Compilers cannot ban legal code

- Could the GSL be part of the standard?
  - Maybe, but we want to use it ***now***
  - The GSL is tiny and written in portable C++11
  - The GSL does not depend on other libraries
  - The GSL is similar to, but not identical to **boost::** and **experimental::** components
    - So they may become standard
- We rely on the standard library

We are not unambitious

- Type and resource safety
  - No leaks
  - No dangling pointers
    - No bad accesses
  - No range errors
  - No use of uninitialized objects
  - No misuse of
    - Casts
    - Unions
- We think we can do it
  - At scale
    - 4+ million C++ Programmers, N billion lines of code
  - Zero-overhead principle

The basic C++ model is now complete

- C++ (using the guidelines) is type safe and resource safe
  - Which other language can claim that?
  - Eliminate dangling pointers
  - Eliminate resource leaks
  - Check for range errors (optionally and cheaply)
  - Check for **nullptr** (optionally and cheaply)
  - Have concepts
- Why not a new C++-like language?
  - Competing with C++ is hard
    - Most attempts fail, C++ constantly improves
  - It would take 10 years (at least)
    - And we would still have lots of C and C++
  - A new C++-like language might damage the C++ community
    - Dilute support, divert resources, distract

To do / being done

- Implementations
  - Static analysis: Microsoft (coming soon), Clang (starting), GCC (?)
  - Support library (GSL):
- Technical specification
- Coding Guidelines
- Popular explanations
- Academic explanations