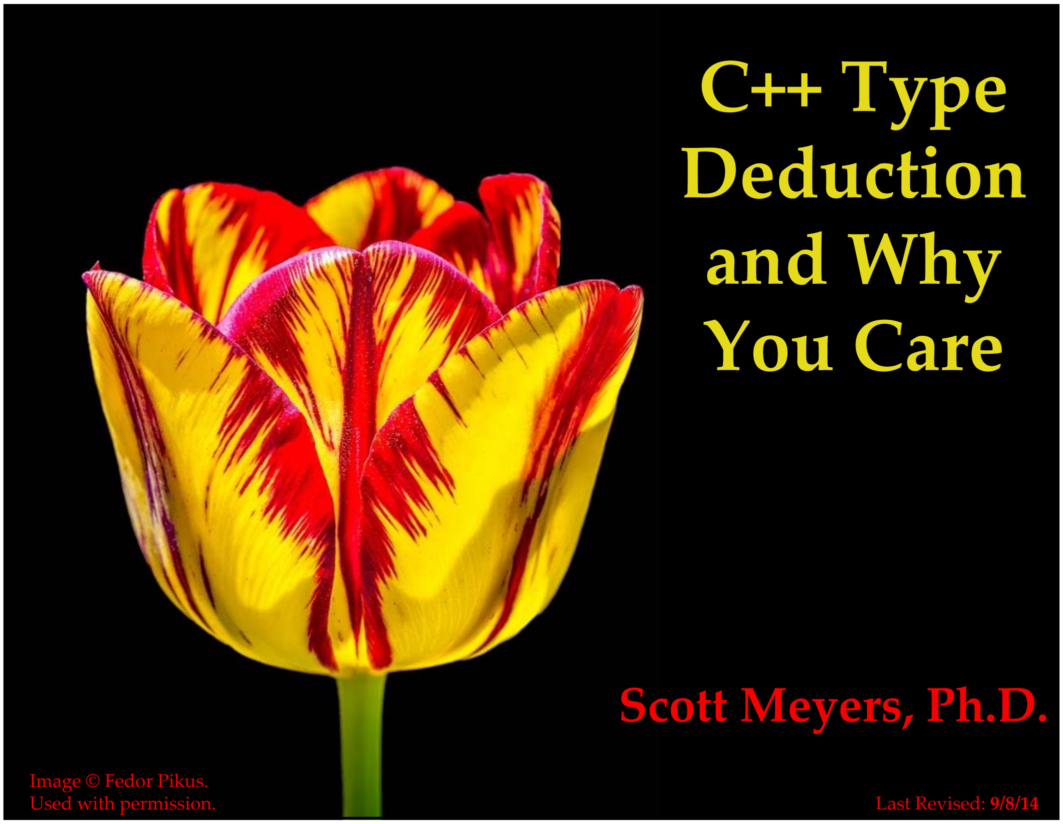

C++ Type Deduction and Why You Care

Scott Meyers, Ph.D.

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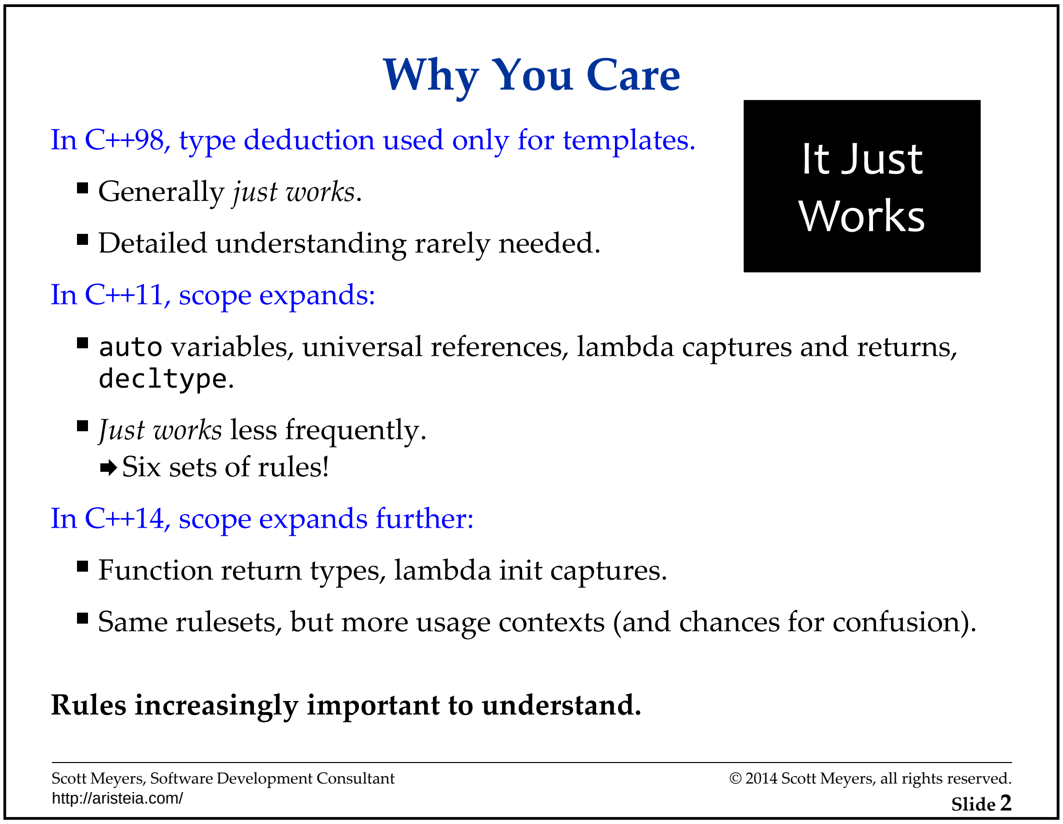
Last Revised: 9/8/14



Why You Care

In C++98, type deduction used only for templates.

- Generally *just works*.
- Detailed understanding rarely needed.

It Just Works

In C++11, scope expands:

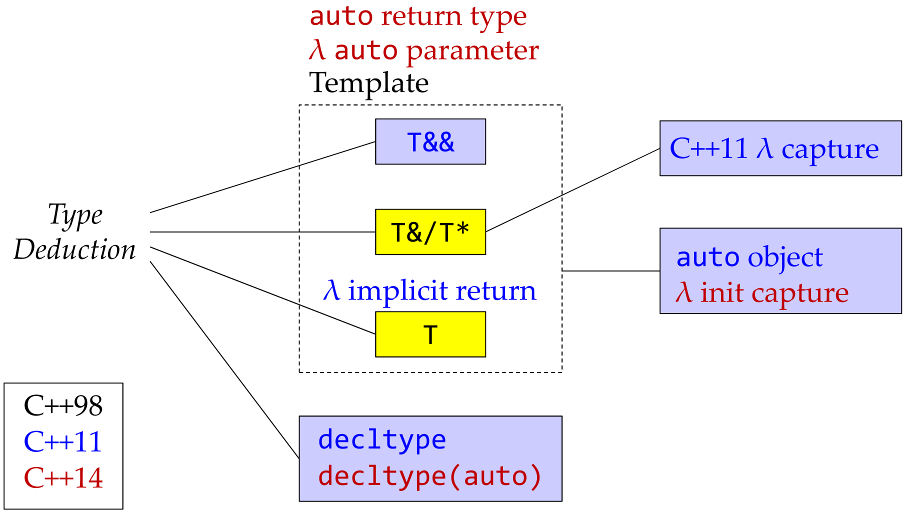
- `auto` variables, universal references, lambda captures and returns, `decltype`.
- *Just works* less frequently.
  - ➡ Six sets of rules!

In C++14, scope expands further:

- Function return types, lambda init captures.
- Same rulesets, but more usage contexts (and chances for confusion).

Rules increasingly important to understand.

The C++ Type Deduction Landscape



“You know, you look just like...”


Jon Bon Jovi

Mick Jagger

Jeff Beck

David Cassidy

He-Man

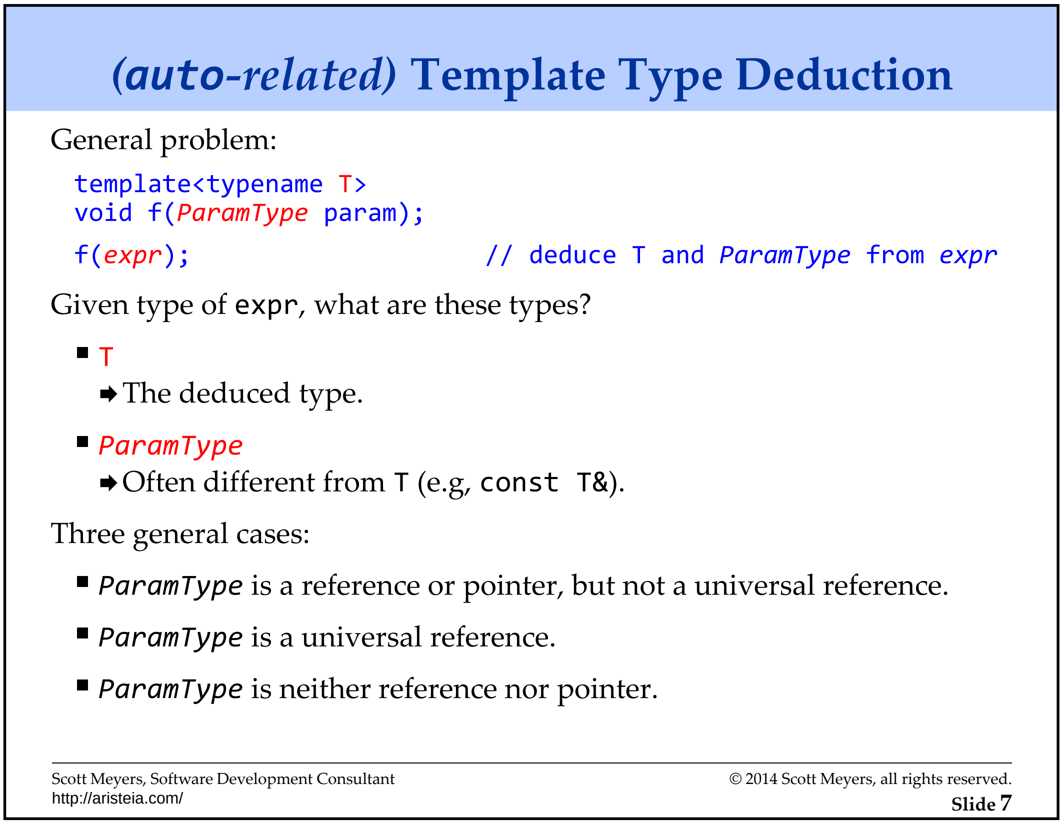
Prince Valiant

Alexander the Great

John Lennon/Bill Gates

ScottMeyersHairPoll.com

And now back to type deduction...



(auto-related) Template Type Deduction

General problem:

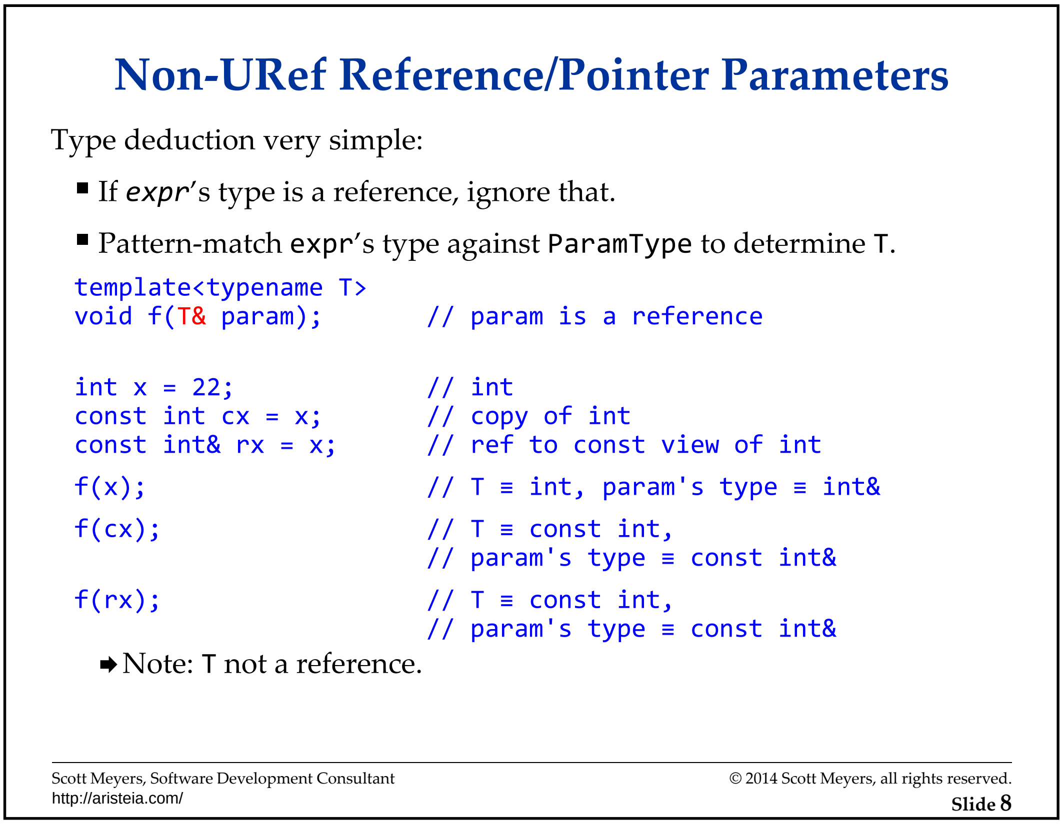
```
template<typename T>
void f(ParamType param);

f(expr);                        // deduce T and ParamType from expr
```

Given type of `expr`, what are these types?

- `T`
  - ➡ The deduced type.
- `ParamType`
  - ➡ Often different from `T` (e.g, `const T&`).

Three general cases:

- `ParamType` is a reference or pointer, but not a universal reference.
- `ParamType` is a universal reference.
- `ParamType` is neither reference nor pointer.



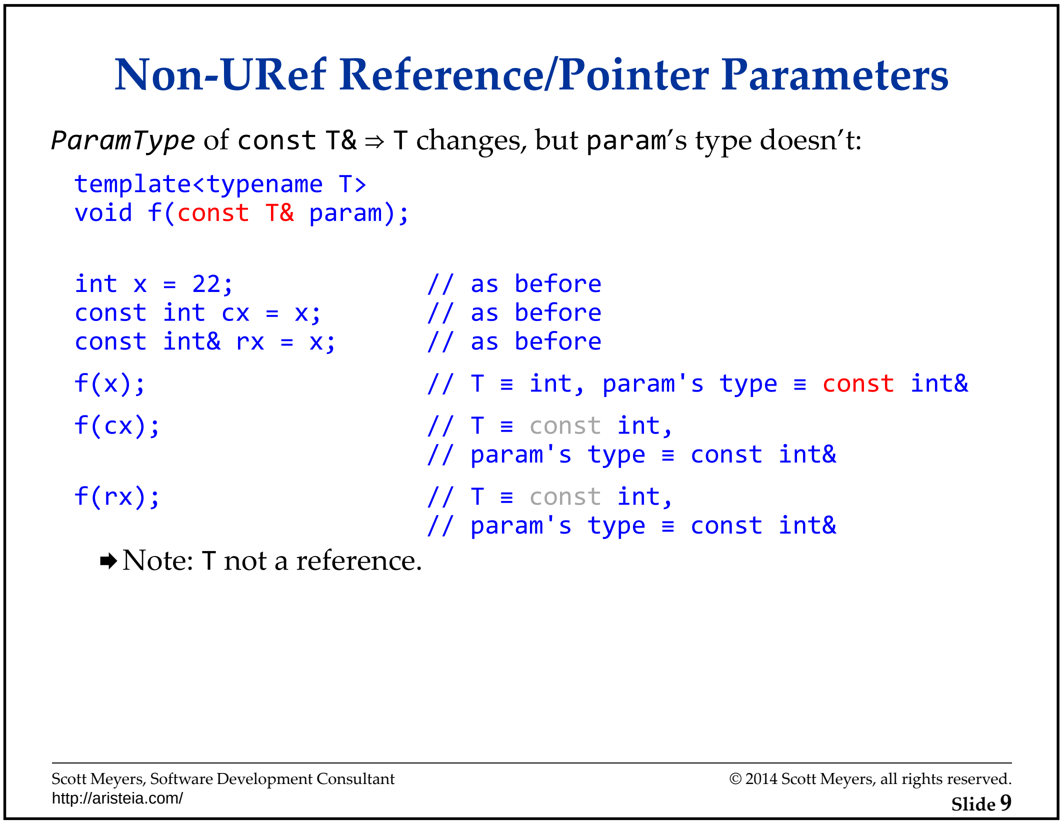
Non-URef Reference/Pointer Parameters

Type deduction very simple:

- If *expr*'s type is a reference, ignore that.
- Pattern-match `expr`'s type against `ParamType` to determine `T`.

```
template<typename T>
void f(T& param);       // param is a reference

int x = 22;             // int
const int cx = x;       // copy of int
const int& rx = x;      // ref to const view of int

f(x);                   // T ≡ int, param's type ≡ int&

f(cx);                  // T ≡ const int,
                        // param's type ≡ const int&

f(rx);                  // T ≡ const int,
                        // param's type ≡ const int&
```

- ➡ Note: `T` not a reference.

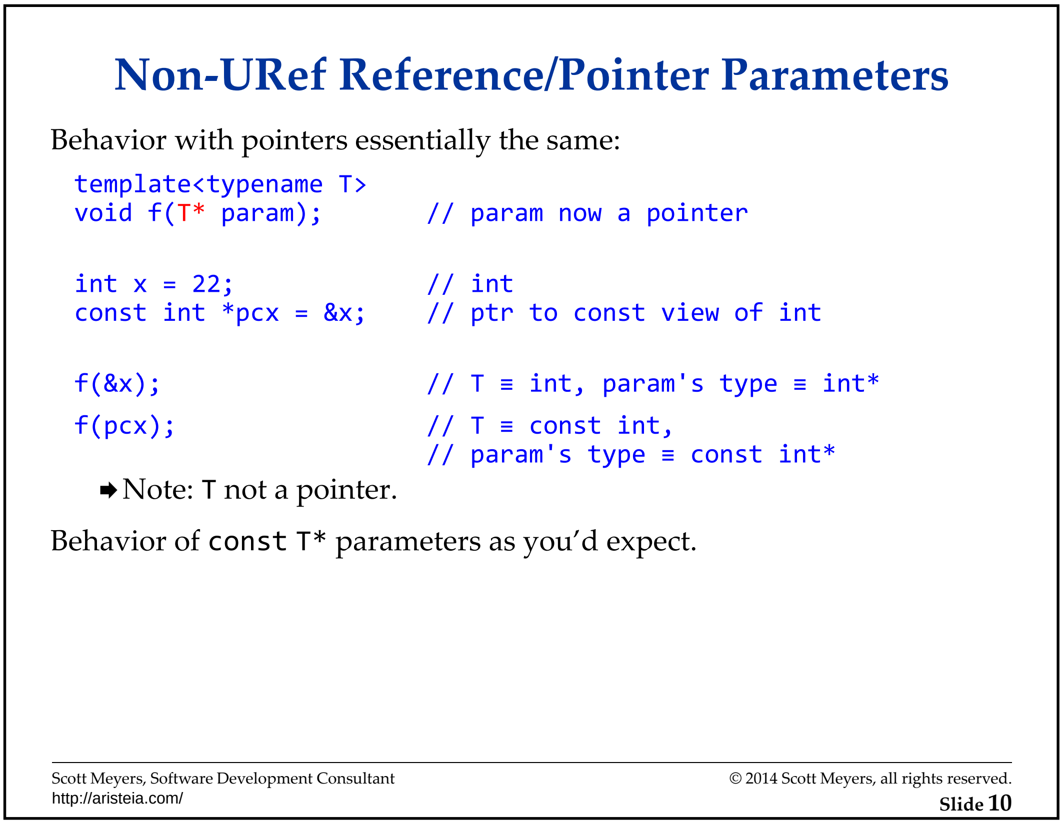


Non-URef Reference/Pointer Parameters

ParamType of `const T&` ⇒ `T` changes, but `param`’s type doesn’t:

```
template<typename T>
void f(const T& param);

int x = 22;                // as before
const int cx = x;          // as before
const int& rx = x;         // as before
f(x);                      // T ≡ int, param's type ≡ const int&
f(cx);                     // T ≡ const int,
                           // param's type ≡ const int&
f(rx);                     // T ≡ const int,
                           // param's type ≡ const int&
```

- ➡ Note: `T` not a reference.



Non-URef Reference/Pointer Parameters

Behavior with pointers essentially the same:

```
template<typename T>
void f(T* param);          // param now a pointer

int x = 22;                // int
const int *pcx = &x;       // ptr to const view of int

f(&x);                     // T ≡ int, param's type ≡ int*
f(pcx);                    // T ≡ const int,
                           // param's type ≡ const int*
```

- ➡ Note: `T` not a pointer.

Behavior of `const T*` parameters as you’d expect.

auto and Non-URef Reference/Pointer Variables

`auto` plays role of `T`:

```
int x = 22;             // as before
const int cx = x;       // as before
const int& rx = x;      // as before

auto& v1 = x;           // v1's type ≡ int& (auto ≡ int)

auto& v2 = cx;          // v2's type ≡ const int&
                        // (auto ≡ const int)

auto& v3 = rx;          // v3's type ≡ const int&
                        // (auto ≡ const int)


const auto& v4 = x;     // v4's type ≡ const int& (auto ≡ int)

const auto& v5 = cx;    // v5's type ≡ const int&
                        // (auto ≡ const int)

const auto& v6 = rx;    // v6's type ≡ const int&
                        // (auto ≡ const int)
```

Yawn

Type deduction for non-URef reference/pointer parameters/variables quite intuitive.

It Just
Works

Universal References

```
template<typename T>
void f(T&& param);
```

```
f(expr);
```

Treated like “normal” reference parameters, except:

- If *expr* is lvalue with deduced type `E`, `T` deduced as `E&`.
  - ➡ Reference-collapsing yields type `E&` for `param`.

```
int x = 22;             // as before
const int cx = x;       // as before
const int& rx = x;      // as before
f(x);       // x is lvalue ⇒ T ≡ int&, param's type ≡ int&
f(cx);      // cx is lvalue ⇒ T ≡ const int&,
            // param's type ≡ const int&
f(rx);      // rx is lvalue ⇒ T ≡ const int&,
            // param's type ≡ const int&
f(22);      // x is rvalue ⇒ no special handling;
            // T ≡ int, param’s type is int&&
```

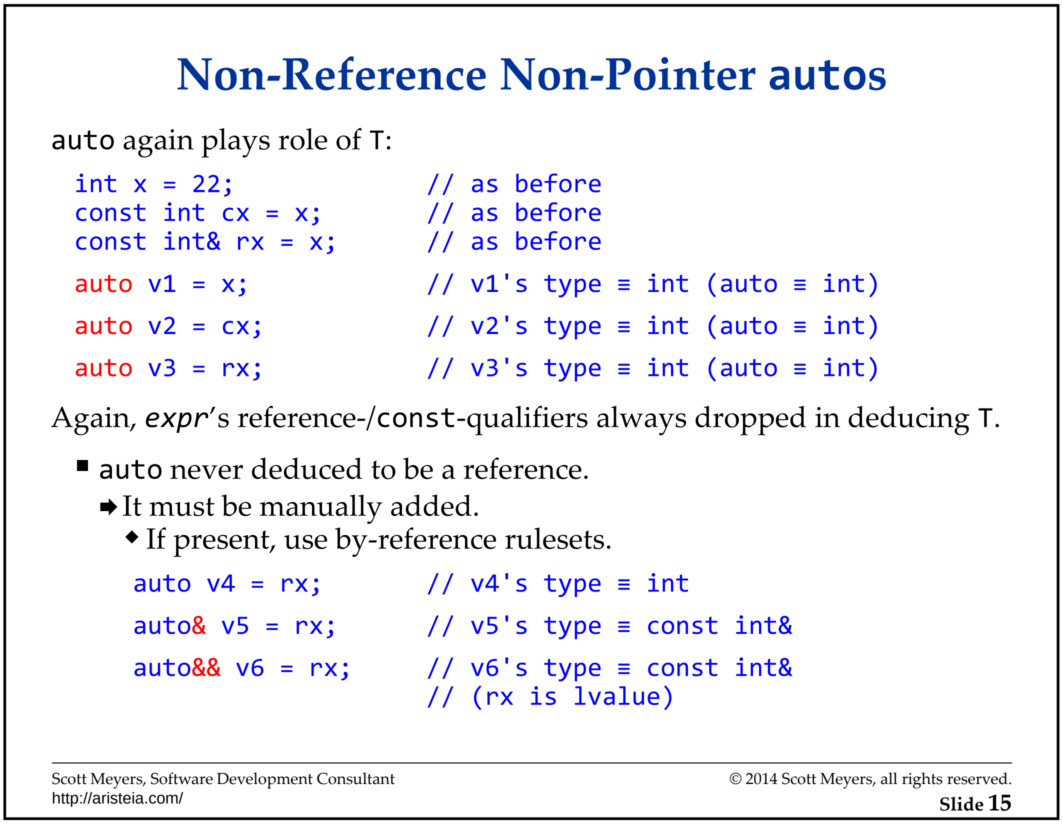
By-Value Parameters

Deduction rules a bit different (vis-à-vis by-reference/by-pointer):

- As before, if *expr*’s type is a reference, ignore that.
- If *expr* is `const` or `volatile`, ignore that.
- `T` is the result.

```
template<typename T>
void f(T param);        // param passed by value

int x = 22;             // as before
const int cx = x;       // as before
const int& rx = x;      // as before
f(x);                   // T ≡ int, param's type ≡ int
f(cx);                  // T ≡ int, param's type ≡ int
f(rx);                  // T ≡ int, param's type ≡ int
```

expr’s reference-/`const`-qualifiers always dropped in deducing `T`.



Non-Reference Non-Pointer `auto`s

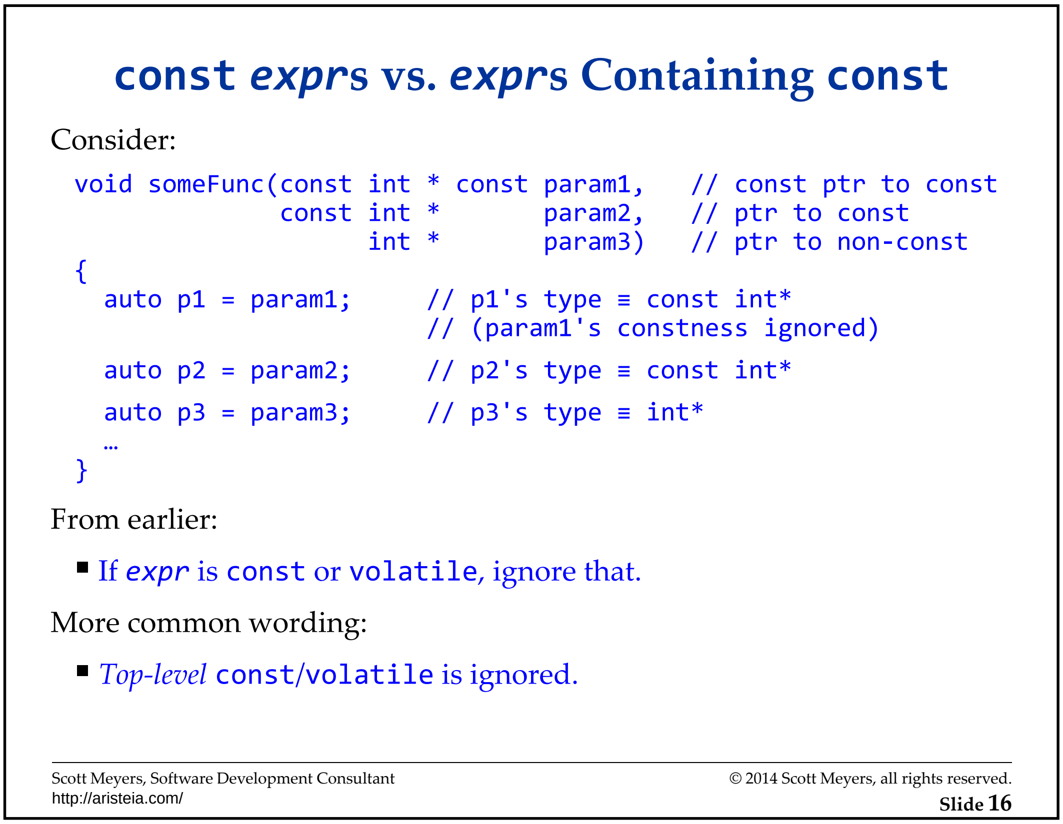
`auto` again plays role of `T`:

```
int x = 22;            // as before
const int cx = x;      // as before
const int& rx = x;     // as before

auto v1 = x;           // v1's type ≡ int (auto ≡ int)

auto v2 = cx;          // v2's type ≡ int (auto ≡ int)

auto v3 = rx;          // v3's type ≡ int (auto ≡ int)
```

Again, *`expr`*'s reference-/`const`-qualifiers always dropped in deducing `T`.

- `auto` never deduced to be a reference.
  - ➡ It must be manually added.
    - ◆ If present, use by-reference rulesets.

```
auto v4 = rx;       // v4's type ≡ int

auto& v5 = rx;      // v5's type ≡ const int&

auto&& v6 = rx;     // v6's type ≡ const int&
                    // (rx is lvalue)
```



`const` *`expr`*s vs. *`expr`*s Containing `const`

Consider:

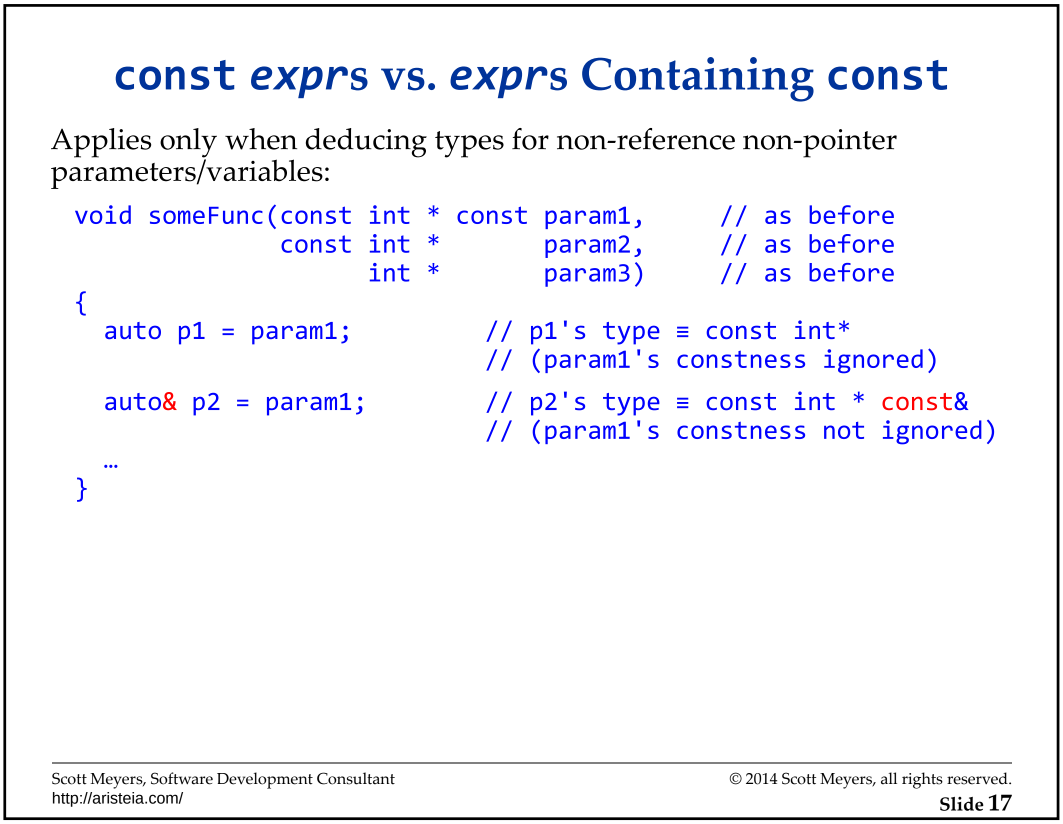
```
void someFunc(const int * const param1,   // const ptr to const
              const int *       param2,   // ptr to const
                    int *       param3)   // ptr to non-const
{
  auto p1 = param1;     // p1's type ≡ const int*
                        // (param1's constness ignored)

  auto p2 = param2;     // p2's type ≡ const int*

  auto p3 = param3;     // p3's type ≡ int*
  …
}
```

From earlier:

- If *`expr`* is `const` or `volatile`, ignore that.

More common wording:

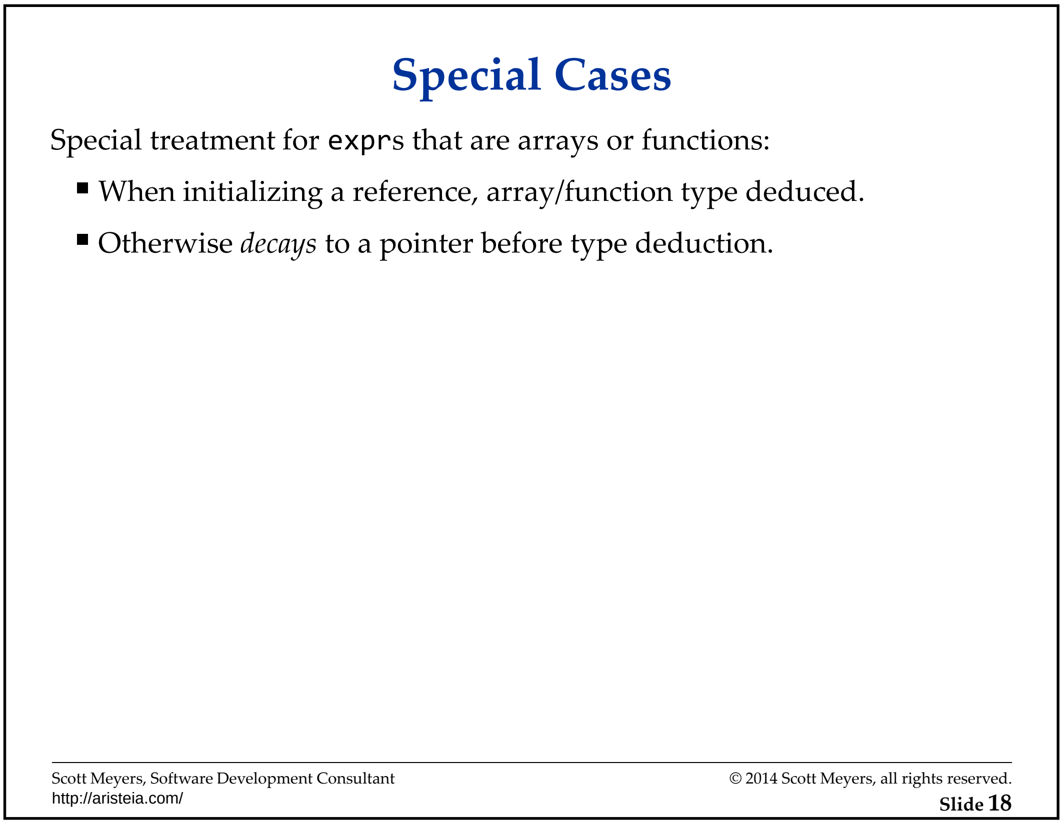
- *Top-level* `const`/`volatile` is ignored.



`const` *expr*s vs. *expr*s Containing `const`

Applies only when deducing types for non-reference non-pointer parameters/variables:

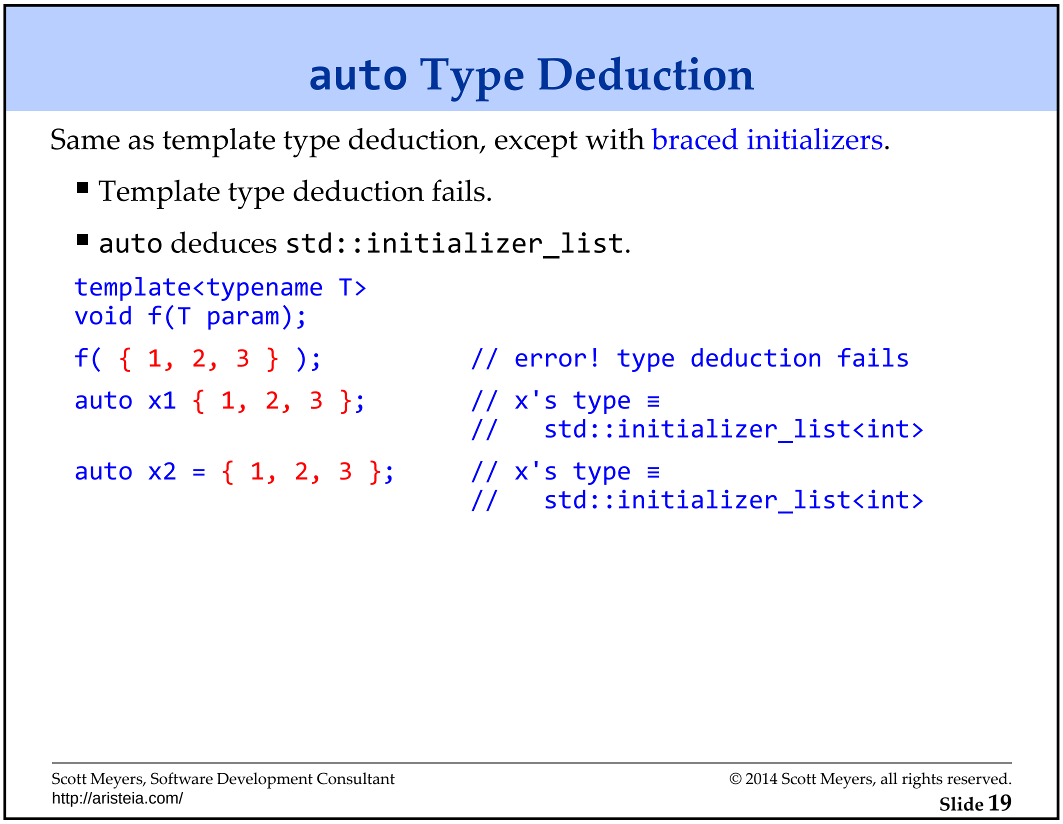
```
void someFunc(const int * const param1,     // as before
              const int *       param2,     // as before
                    int *       param3)     // as before
{
  auto p1 = param1;         // p1's type ≡ const int*
                            // (param1's constness ignored)

  auto& p2 = param1;        // p2's type ≡ const int * const&
                            // (param1's constness not ignored)

  …
}
```



Special Cases

Special treatment for `expr`s that are arrays or functions:

- When initializing a reference, array/function type deduced.
- Otherwise *decays* to a pointer before type deduction.

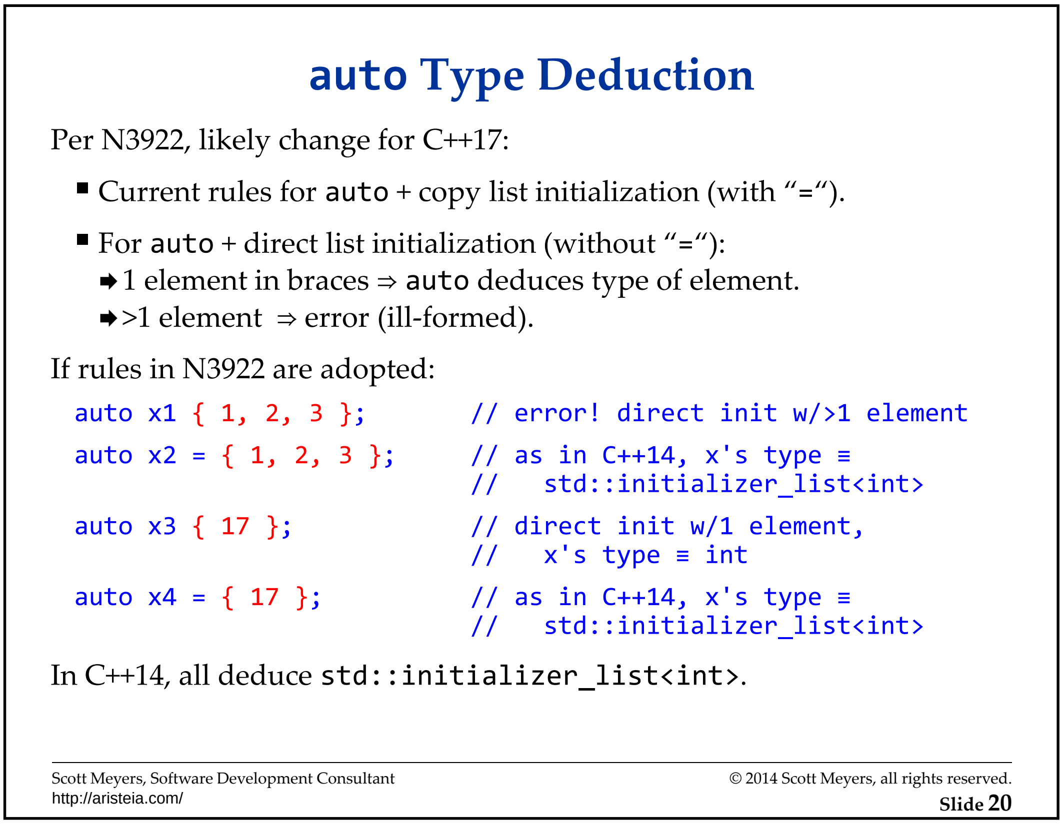


auto Type Deduction

Same as template type deduction, except with braced initializers.

- Template type deduction fails.
- `auto` deduces `std::initializer_list`.

```
template<typename T>
void f(T param);

f( { 1, 2, 3 } );          // error! type deduction fails

auto x1 { 1, 2, 3 };       // x's type ≡
                           //   std::initializer_list<int>

auto x2 = { 1, 2, 3 };     // x's type ≡
                           //   std::initializer_list<int>
```



auto Type Deduction

Per N3922, likely change for C++17:

- Current rules for `auto` + copy list initialization (with "=").
- For `auto` + direct list initialization (without "="):
  - 1 element in braces ⇒ `auto` deduces type of element.
  - >1 element ⇒ error (ill-formed).

If rules in N3922 are adopted:

```
auto x1 { 1, 2, 3 };       // error! direct init w/>1 element

auto x2 = { 1, 2, 3 };     // as in C++14, x's type ≡
                           //   std::initializer_list<int>

auto x3 { 17 };            // direct init w/1 element,
                           //   x's type ≡ int

auto x4 = { 17 };          // as in C++14, x's type ≡
                           //   std::initializer_list<int>
```

In C++14, all deduce `std::initializer_list<int>`.

`auto` Type Deduction

Who cares? C++17 is a long ways away!

- The current MSVC CTP implements N3922...

Lambda Capture Type Deduction

Three kinds of capture:

- **By reference**: uses template type deduction (for reference params).
- **C++14's init capture**: uses `auto` type deduction.
- **By value**: uses template type deduction, except cv-qualifiers are retained:

```
{
  const int cx = 0;
  auto lam = [cx] { ... };
  ...
}
class UpToTheCompiler {
private:
  const int cx;
  ...
};
```

Lambda Capture Type Deduction

Simple by-value capture ≠ by-value init capture:

```
{
  const int cx = 0;
  auto lam = [cx]{ ... };
  ...
}
class UpToTheCompiler11 {
private:
  const int cx;
  ...
};
```

```
{
  const int cx = 0;
  auto lam = [cx = cx]{ ... };
  ...
}
class UpToTheCompiler14 {
private:
  int cx;
  ...
};
```

Lambda Capture Type Deduction

`const` retention normally masked by default `const`ness of `operator()`:

```
{
  int cx = 0;                              // now non-const
  auto lam = [cx] { cx = 10; };            // error!
  ...
}
class UpToTheCompiler {
public:
  void operator()() const { cx = 10; }    // cause of error
private:
  int cx;
};
```

Lambda Capture Type Deduction

`mutable` lambdas reveal the truth:

```
{
  const int cx = 0;                          // now const

  auto lam = [cx] mutable { cx = 10; };     // still error!
  ...
}
class UpToTheCompiler {
public:
  void operator()() { cx = 10; }

private:
 const int cx;                               // cause of error
};
```

Gratuitous Animal Photo

Ring-Tailed Lemurs

Image © Iain Wanless (Reemul @ flickr)

Observing Deduced Types

During compilation:

- Use declared-only template with type of interest:

```
template<typename T>                 // declaration for TD;
class TD;                            // TD == "Type Displayer"

template<typename T>                 // template w/types
void f(T& param)                     // of interest
{
  TD<T> tType;                       // cause T to be shown
  TD<decltype(param)> paramType;     // ditto for param's type
  …
}
```

Observing Deduced Types

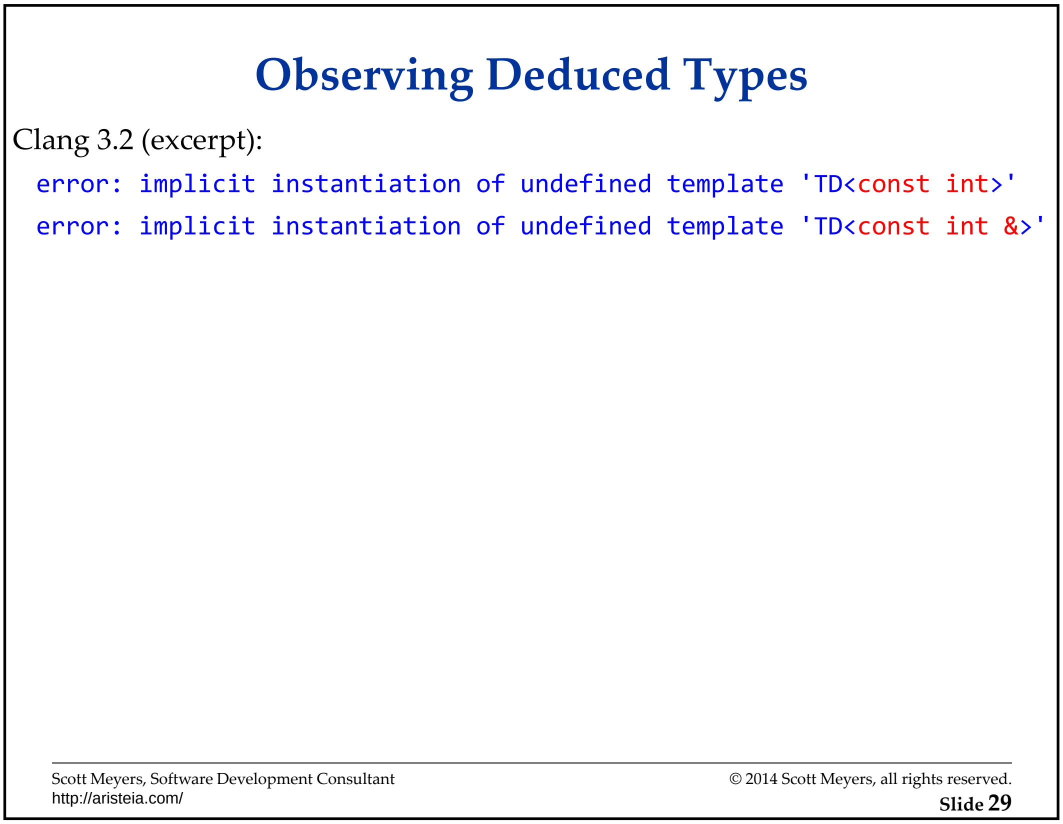
```
int x = 22;              // as before
const int& rx = x;       // as before

f(rx);                   // compiler diagnostics show types
```

gcc 4.8 (excerpt):

```
error: 'TD<const int> tType' has incomplete type

error: 'TD<const int &> paramType' has incomplete type
```

VS 2013 (excerpt):

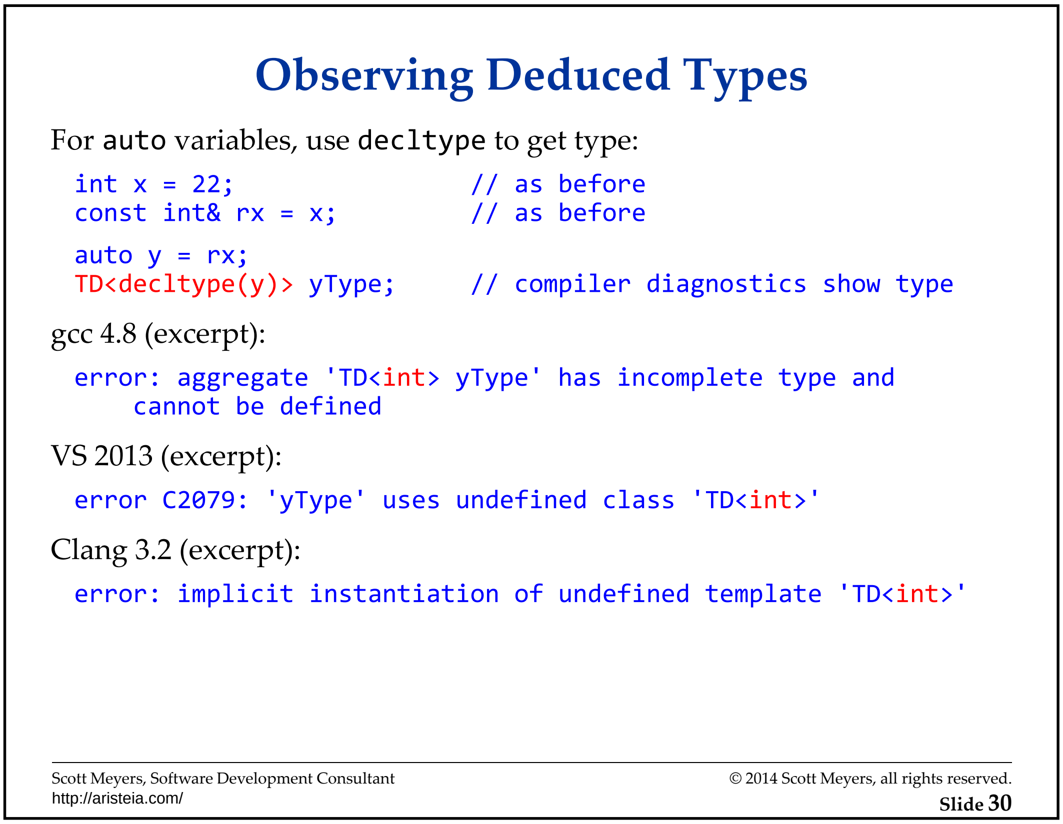
```
error C2079: 'tType' uses undefined class 'TD<T>'
        with
        [
            T=const int
        ]
error C2079: 'paramType' uses undefined class 'TD<T &>'
        with
        [
            T=const int
        ]
```



Observing Deduced Types

Clang 3.2 (excerpt):

```
error: implicit instantiation of undefined template 'TD<const int>'
error: implicit instantiation of undefined template 'TD<const int &>'
```



Observing Deduced Types

For `auto` variables, use `decltype` to get type:

```
int x = 22;                  // as before
const int& rx = x;           // as before

auto y = rx;
TD<decltype(y)> yType;       // compiler diagnostics show type
```

gcc 4.8 (excerpt):

```
error: aggregate 'TD<int> yType' has incomplete type and
    cannot be defined
```

VS 2013 (excerpt):

```
error C2079: 'yType' uses undefined class 'TD<int>'
```

Clang 3.2 (excerpt):

```
error: implicit instantiation of undefined template 'TD<int>'
```

Observing Deduced Types

At runtime, things a bit trickier.

Consider:

```
template<typename T>
void f(const T& param);             // template we'll call

class Widget { … };

std::vector<Widget> createVec();    // factory function

const auto vw = createVec();        // init vw w/factory return

if (!vw.empty()) {
  f(&vw[0]);                        // in f, what are T and
  …                                 // param's type?
}
```

Observing Deduced Types

Avoid `std::type_info::name`.

- Language rules require incorrect results in some cases!

Given

```
template<typename T>
void f(const T& param)
{
  using std::cout;

  cout << "T =     " << typeid(T).name() << '\n';      // show T

  cout << "param = " << typeid(param).name() << '\n';  // show
  …                                                    // param's
}                                                      // type
```

compilers report `param`'s type as `const Widget *`.

- Correct type is `const Widget * const &`.

Observing Deduced Types

Boost.TypeIndex provides accurate information:

```
#include <boost/type_index.hpp>

template<typename T>
void f(const T& param)
{
  using boost::typeindex::type_id_with_cvr;
  using std::cout;

  cout << "T =     "                                         // show
       << type_id_with_cvr<T>().pretty_name() << '\n';       // T

  cout << "param = "                                         // show
       << type_id_with_cvr<decltype(param)>().pretty_name()  // param's
       << '\n';                                              // type
  …
}
```

gcc/Clang output:

```
T =     Widget const*
param = Widget const* const&
```

VS 2013 essentially the same.

`decltype` Type Deduction

`decltype(`*name*`)` ≡ declared type of *name*. Unlike `auto`:

- Never strips `const`/`volatile`/references.

```
int x = 10;                 // decltype(x) ≡ int
const auto& rx = x;         // decltype(rx) ≡ const int&
```

`decltype` Type Deduction

`decltype(`*`lvalue expr of type T`*`)` ≡ `T&`.

- Unsurprising. Almost all such expressions really have type `T&`.

```
const std::vector<Widget>&        // return type is lvalue
  findVec(const VecHandle&);      // expr and has lvalue-ref
                                  // type
```

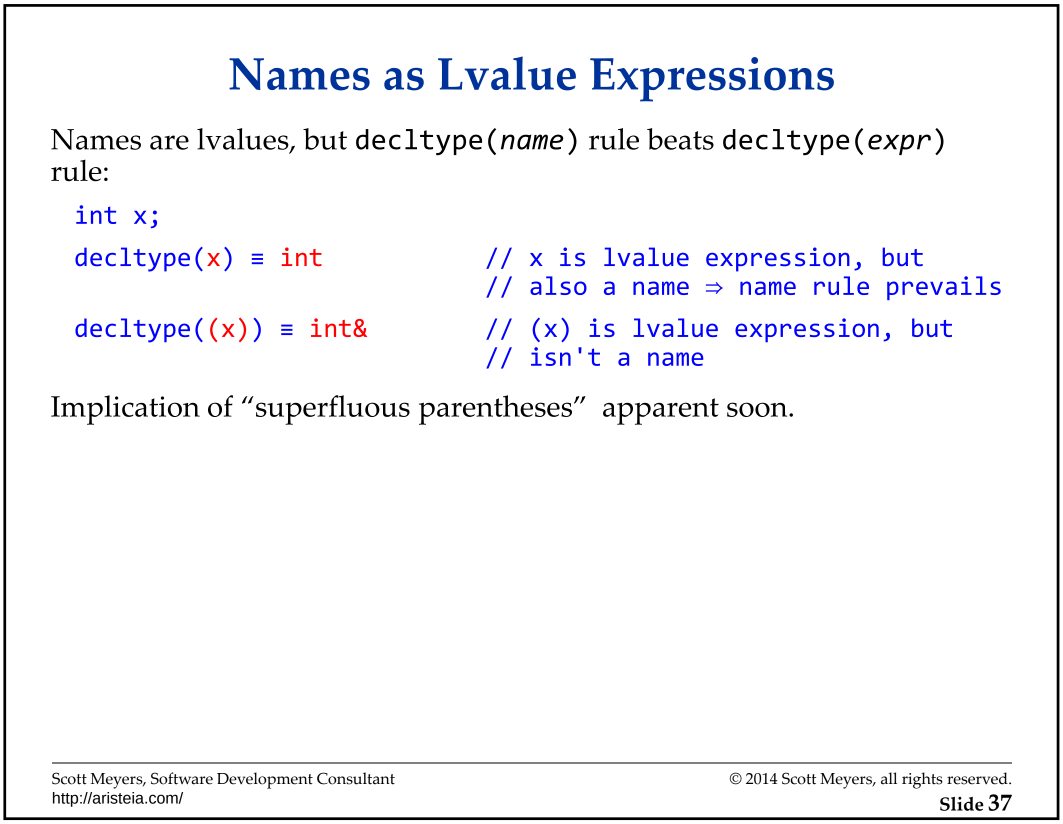
- ➡ Exceptions act as if they did.

```
int arr[10];

arr[0] = 5;                      // arr[0]'s type is int,
                                 // but it acts like int&

decltype(arr[0]) ≡ int&          // because arr[0] is
                                 // lvalue expression
```

`decltype` Type Deduction

Full rules for `decltype` more complex.

- Relevant only to hard-core library developers.
- Rules we’ve seen suffice for almost everybody almost all the time.

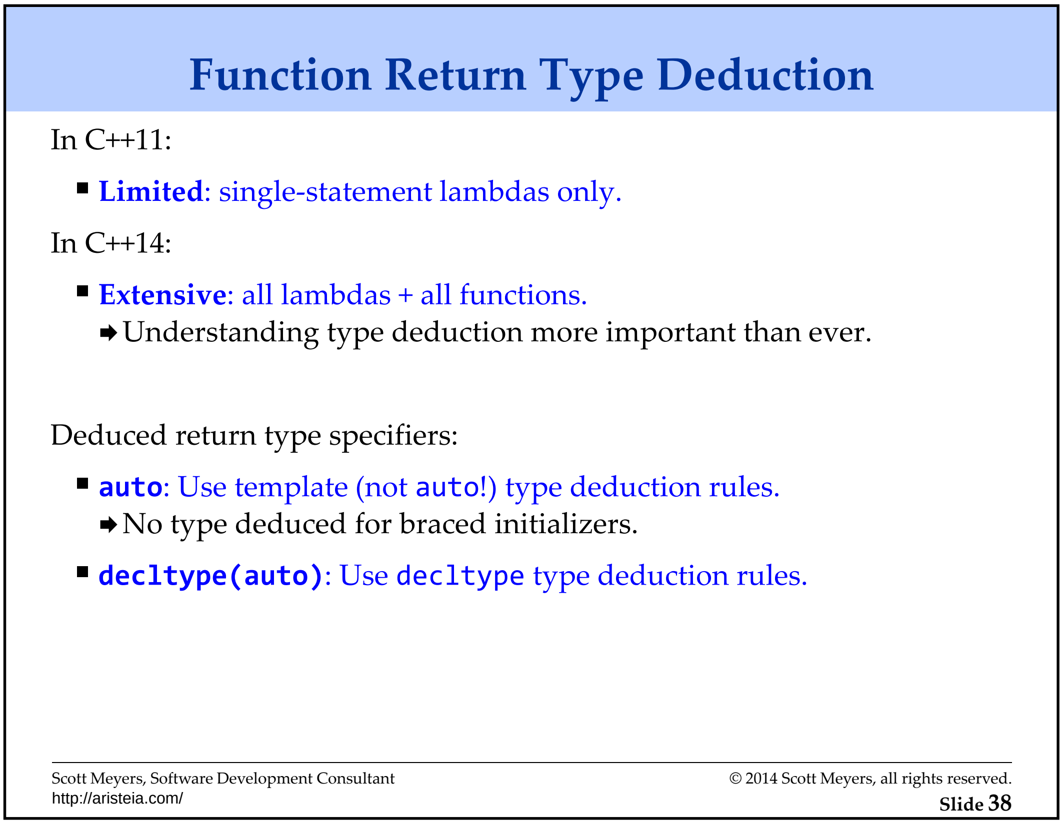


Names as Lvalue Expressions

Names are lvalues, but `decltype(name)` rule beats `decltype(expr)` rule:

```
int x;
decltype(x) ≡ int            // x is lvalue expression, but
                             // also a name ⇒ name rule prevails
decltype((x)) ≡ int&         // (x) is lvalue expression, but
                             // isn't a name
```

Implication of "superfluous parentheses" apparent soon.



Function Return Type Deduction

In C++11:

- **Limited**: single-statement lambdas only.

In C++14:

- **Extensive**: all lambdas + all functions.
  - ➡ Understanding type deduction more important than ever.

Deduced return type specifiers:

- **`auto`**: Use template (not `auto`!) type deduction rules.
  - ➡ No type deduced for braced initializers.
- **`decltype(auto)`**: Use `decltype` type deduction rules.

Function Return Type Deduction

Sometimes `auto` is correct:

```
auto lookupValue( context information )
{
  static std::vector<int> values = initValues();
  int idx = compute index into values from context info;
  return values[idx];
}
```

- Returns `int`.
- `decltype(auto)` would return `int&`.
  - ➡ Would permit caller to modify `values`!

```
    lookupValue(myContextInfo) = 0;       // shouldn't compile!
```

Function Return Type Deduction

Sometimes `decltype(auto)` is correct:

```
decltype(auto) authorizeAndIndex(std::vector<int>& v, int idx)
{
  authorizeUser();
  return v[idx];
}
```

- Returns `int&`.
- `auto` would return `int`.
  - ➡ Wouldn't permit caller to modify `std::vector`:

```
    authorizeAndIndex(myVec, 10) = 0;        // should compile!
```

Function Return Type Deduction

`decltype(auto)` sensitive to function implementation:

```
decltype(auto) lookupValue( context information )
{
  static std::vector<int> values = initValues();
  int idx = compute index into values from context info;

  auto retVal = values[idx];      // retVal's type is int

  return retVal;                  // returns int
}

decltype(auto) lookupValue( context information )
{
  static std::vector<int> values = initValues();
  int idx = compute index into values from context info;

  auto retVal = values[idx];      // retVal's type is int

  return (retVal);                // returns int& (to local
}                                 // variable!)
```

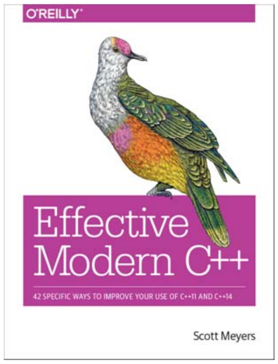
Function Return Type Deduction

Rules of thumb:

- Use `auto` if a reference type would never be correct.
- Use `decltype(auto)` only if a reference type could be correct.

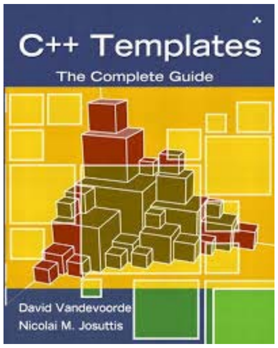
Further Information

- *Effective Modern C++*, Scott Meyers, O'Reilly, anticipated October 2014.
  - ➡ Chapter 1 covers type deduction.
    - ◆ Available for free download at oreilly.com.
- "C++ auto and decltype Explained," Thomas Becker, `thbecker.net`, May 2013.
- "Universal References in C++11," Scott Meyers, *isocpp.org Blog*, November 2012.
- "New Rules for auto deduction from braced-init-list," James Dennett, Standardization Committee paper N3922, 13 February 2014.
- "If braced initializers have no type, why is the committee so insistent on deducing one for them?," Scott Meyers, *The View from Aristeia* (blog), 8 March 2014.



Further Information

- "Capture Quirk in C++14," Scott Meyers, *The View From Aristeia* (blog), 3 February 2014.
  - ➡ Type deduction for by-value lambda captures vs. for init captures.
- *C++ Templates*, David Vandevoorde and Nicolai M. Josuttis, Addison-Wesley, 2003.
  - ➡ Comprehensive coverage of C++98 rules.
- *Boost.TypeIndex 4.0*, Antony Polukhin, boost.org.



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