AUTO & DECLTYPE

auto and decltype specifiers by Prasanna Ghali

Plan for Today

- How does `auto` work
- How does `decltype` work

auto: The Basics (1/7)

- We write code like this all the time ...

```
std::vector<int> vi;
// ...

for (std::vector<int>::const_iterator cit = std::cbegin(vi);
     cit != std::cend(vi);
     ++cit) {
  std::cout << *cit;
}
```

auto: The Basics (2/7)

- Next, consider this code …

```
std::vector<int> vi;
// ...
for (std::vector<int>::iterator it = std::begin(vi);
      it != std::end(vi);
      ++it) {
  std::cin >> *it;
}
```

- Quite annoying for programmer to explicitly write type of variable `it` when compiler knows type `it` should be!!!

auto: The Basics (3/7)

- Since C++11, language shares with programmer type of initializing expression `std::begin(vi)`
- Since C++11, you can declare variable without specifying its type by using `auto`

```
std::vector<int> vi;
// ...
for (auto it = std::begin(vi); it != std::end(vi); ++it) {
  std::cin >> *it;
}
```

auto: The Basics (4/7)


```
double f(); // f() returns value of type double
auto d {f()};     // f() and d have type double
auto i {42};      // 42 and i have type int
auto flag{false}; // false and flag has type bool

// additional qualifiers are allowed
static auto pi = 3.1428;

std::vector<std::string> vs;
// using auto is especially useful where the type
// is a pretty long and/or complicated expression
// pos has type std::vector<std::string>::iterator
auto pos = std::begin(vs);
```

auto: The Basics (5/7)

- auto doesn't change fact that C++ is strongly typed

```
double f();
auto d {f()}; // f() and d have type double
```

  - Variable d has result type of expression in initializer, and this type will never change afterward
  - In Python, variable d will have *dynamic type*: an assignment to d can change type of d to that of assigned expression

auto: The Basics (6/7)

- Initializer is required since type of variable declared with auto is deduced from its initializer

```
auto a;        // error: don't know type of a
a = f(x, y); // too late ...

// we can declare multiple auto variables in same statement
// as long as all initializers are expressions of same type
auto i {2*7.5}, j {std::sqrt(3.9)}; // ok: both are double
auto m {2*4},   n {std::sqrt(3.9)}; // error: m is int,
                                    // n is double
auto o {2*4}, p;  // error: p not initialized
auto q {f(i, j)}; // type of result of f(i, j)
```

auto: The Basics (7/7)

- Can qualify auto with const and/or reference qualifiers:

```
auto i{2*7}; // i is int variable initialized to 14

const auto ci  {i}; // ci's type deduced as int const
auto const ci2 {i}; // ci2's type deduced as int const

auto& ri {i};            // ri's type deduced as int&
auto const& rci  {i}; // rci's type deduced as int const&
const auto& rci2 {i}; // same as rci
```

auto: Beyond The Basics (1/4)

- Consider this example of using auto:

```
int x{};                // x is int initialized to 0
int const& rcx{x};      // rcx is read-only reference of x
x = 21;
auto something{rcx};    // what is the type of something?
++x;
std::cout << something; // what is value written to stdout?
++something;            // will this compile?
```

Since declared type of rcx is int const& and initializing expression for something is rcx, you might think that type of something is int const&.
Not so.
It turns out type of something is deduced as int.

auto: Beyond The Basics (2/4)

- Consider more scenarios that use auto:

```
char str[6] {"hello"}; // str is array of 6 char elements

auto str2 {"hello"}; // what is type of str2?
auto str3 = "world"; // what is type of str3?
auto str4 {str};       // what is type of str4?
auto ia = {1,2,3,4}; // what is type of ia?
```

Both `"hello"` and `"world"` are of type `char const [6]` which evaluates to `char const*`; therefore `str2` and `str3` are both deduced to have type `char const*`.
`str` evaluates to type `char*`; therefore `str4` has type `char*`.
With braced initializers `{1,2,3,4}`, `ia`'s type is deduced as `std::initializer_list<int>`.

auto: Beyond The Basics (3/4)

- What about expressions with auto&&?

```
double f(int x, int y) { return static_cast<double>(x+y); }
template <typename T> T& g(T& x) { return ++x; }

// which of following declaration statements compile
// and if they compile, what is type of variable?

auto   i {42};          // i has type int
auto&& rri {f(i, i)}; // what is type of rri?
auto&& rri2 {42};      // what is type of rri2?
auto&& rri3 {i};       // what is type of rri3?
auto&& rri4 {g(42)};  // what is type of rri4?
auto&& rri5 {g(i)};   // what is type of rri5?
```

auto: Beyond The Basics (4/4)

- What about expressions with auto&&?

```
double f(int x, int y) { return static_cast<double>(x+y); }
template <typename T> T& g(T& x) { return ++x; }

// which of following declaration statements compile
// and if they compile, what is type of variable?

auto   i {42};           // i has type int
auto&& rri {f(i, i)};    // rri  deduced as rvalue reference
auto&& rri2 {42};        // rri2 deduced as rvalue reference
auto&& rri3 {i};         // rri3 deduced as lvalue reference
auto&& rri4 {g(42)};     // error: 42 is not an lvalue
auto&& rri5 {g(i)};      // rri5 deduced as lvalue reference
```

How to Understand `auto` Declarations? (1/6)

- In previous examples, we saw that `auto` type specifier is used in number of places to deduce type of variable from its initializer
- `auto` type deduction *is* template type deduction
- There is direct algorithmic transformation from template type deduction to `auto` type deduction

How to Understand auto Declarations? (2/6)


```
auto        x {42}; // what is type deduced for x???
const auto  cx {x}; // what is type deduced for cx???
const auto& rx {x}; // what is type deduced for rx???
```

- To deduce types for x, cx, and rx in these examples, compilers act as if there were a function template for each declaration as well as a call to that template with corresponding initializing expression

How to Understand auto Declarations? (3/6)

- Type deduced for `identifier` is type deduced for `param` through template type deduction

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

// call f with some  expression
f( expr );
```

```
type specifier with auto identifier = initializer;
```

How to Understand auto Declarations? (4/6)


```
auto  x {42}; // what is type deduced for x???

template <typename T>      // conceptual template for
void func_for_x(T param); // deducing x's type
func_for_x(42);            // conceptual call: param's
                           // deduced type is x's type
```

How to Understand auto Declarations? (5/6)


```
auto         x {42}; // what is type deduced for x???

template <typename T>                // conceptual template for
void func_for_x(T param);            // deducing x's type
func_for_x(42);                      // conceptual call: param's
                                     // deduced type is x's type

const auto  cx {x}; // what is type deduced for cx???

template <typename T>                // conceptual template for
void func_for_cx(const T param);     // deducing cx's type
func_for_cx(x);                      // conceptual call: param's
                                     // deduced type is cx's type
```

How to Understand auto Declarations? (6/6)


```
auto         x {42}; // what is type deduced for x
template <typename T>                 // conceptual template for
void func_for_x(T param);             // deducing x's type
func_for_x(42);                       // conceptual call: param's
                                      // deduced type is x's type

const auto  cx {x}; // what is type deduced for cx
template <typename T>                 // conceptual template for
void func_for_cx(const T param);      // deducing cx's type
func_for_cx(x);                       // conceptual call: param's
                                      // deduced type is cx's type

const auto& rx {x}; // what is type deduced for rx
template <typename T>                 // conceptual template for
void func_for_rx(const T& param);     // deducing rx's type
func_for_rx(x);                       // conceptual call: param's
                                      // deduced type is rx's type
```

auto Type Deduction: Cases

- Just as with template type deduction, auto type deduction has three cases to consider:
  - *type specifier* is pointer or reference type
  - *type specifier* is neither a pointer nor reference
  - *type specifier* is forwarding reference

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

// call f with some  expression
f( expr );
```

```
type specifier with auto identifier = initializer;
```

auto Type Deduction: Examples (1/2)

- Three cases to consider:
  - *type specifier* is pointer or reference type
  - *type specifier* is neither a pointer nor reference
  - *type specifier* is forwarding reference

```
// case 2
auto x {27};            // x:  ???
auto const cx {x};      // cx: ???

// case 1
auto const& rx {x};     // rx: ???

// case 3
auto&& ref1 {x};        // ref1: ???
auto&& ref2 {cx};       // ref2: ???
auto&& ref3 {27};       // ref3: ???
```

auto Type Deduction: Examples (2/2)


```
// arrays
char const name[] {"hello"};
auto  arr1 {name};          // arr1: ???
auto& arr2 {name};          // arr2: ???

// functions
void  func(int, double);
auto  fun1 {func};          // fun1: ???
auto& fun2 {func};          // fun2: ???
```

auto Type Deduction: Exception (1/5)

- auto works like template type deduction
- Except for one way they differ
- Start with observation that if you want to initialize an int
  - C++98 gives 2 choices
  - C++11 gives 4 choices

```
// C++98 initialization syntax
int x1 = 27;
int x2 (27);
```

```
// C++11 initialization syntax
int x1 = 27;
int x2 (27);
int x2 = {27};
int x2 {27};
```

auto Type Deduction: Exception (2/5)

- We can initialize `int`s in 4 ways but replacing `int` with `auto` is not *always* equivalent!!!

```
// C++11 initialization syntax
int x1 = 27;
int x2 (27);
int x3 = {27};
int x4 {27};
```

```
// All declarations will compile after
// substitution of int with auto
auto x1 = 27;
auto x2 (27);
auto x3 = {27};
auto x4 {27};
```

auto Type Deduction: Exception (3/5)

- When initializer for `auto`-declared variable is enclosed in braces, deduced type is `std::initializer_list`

```
auto x1 = 27;   // type is int, value is 27
auto x2 (27);   // type is int, value is 27
auto x3 = {27}; // type is std::initializer_list<int>
                // value is {27}
auto x4 {27};   // type is int, value is 27
```

auto Type Deduction: Exception (4/5)

- Treatment of braced initializers is only way in which auto type deduction and template type deduction differ!!!

```
// we know x's type is deduced as std::initializer_list<int>
auto x = {11, 23, 9};

// template equivalent to x's declaration
template <typename T> void f(T param);
f({11, 23, 9}); // error: cannot deduce type for T

// template for which template type deduction will work
template <typename T> void g(std::initializer_list<T> param);
g({11, 23, 9}); // ok: T deduced as int and
                // param’s type is initializer_list<int>
```

auto Type Deduction: Exception (5/5)

- So only real difference between auto and template type deduction is that auto assumes braced initializer represents std::initializer_list but template type deduction doesn't!!!
- Remember that if you declare a variable using auto and you initialize it with braced initializer, deduced type will always be std::initializer_list

Prefer auto Over Explicit Type Declarations (1/9)

- Less verbose declarations

```
// print values of all elements in range [b, e)
template <typename It>
void print(It b, It e) {
  while (b != e) {
    typename std::iterator_traits<It>::value_type val = *b;
    std::cout << val << ' ';
    ++b;
  }
  std::cout << "\n";
}

std::vector<std::string> vs{"a","b","c","d"};
print(std::begin(vs), std::end(vs));

std::deque<int> di{1, 2, 3, 4, 5, 6};
print(std::begin(di), std::end(di));
```

Prefer auto Over Explicit Type Declarations (2/9)

- Less verbose declarations

```
// print values of all elements in range [b, e)
template <typename It>
void print(It b, It e) {
  while (b != e) {
    auto val = *b;
    std::cout << val << ' ';
    ++b;
  }
  std::cout << "\n";
}

std::vector<std::string> vs{"a","b","c","d"};
print(std::begin(vs), std::end(vs));

std::deque<int> di{1, 2, 3, 4, 5, 6};
print(std::begin(di), std::end(di));
```

Prefer auto Over Explicit Type Declarations (3/9)

- Prevents uninitialized variables

```
int  i1;      // potentially uninitialized
auto i2;      // error: initializer required
auto i3 {0}; // ok: i3's value is well defined
```

```
// use of auto prevents uninitialized local variables
template <typename It>
void print(It b, It e) {
  while (b != e) {
    auto val = *b;
    std::cout << val << ' ';
    ++b;
  }
  std::cout << "\n";
}
```

Prefer auto Over Explicit Type Declarations (4/9)

- Prevents “type shortcuts”

```
std::vector<std::string> vs{"a","b","c","d"};

// fairly common type shortcut that might cause
// problems on 64-bit machines ...
unsigned sz = vs.size();

// programmer should have used explicit type ...
std::vector<std::string>::size_type sz2 = vs.size();

// however, many programmers are unaware of the official
// return type of vs.size() ...
// using auto ensures you don't have to spend time
// remembering official return type and understanding
// 32-bit vs 64-bit issues ...
auto sz3 = vs.size(); // sz3's type is official return type ...
```

Prefer auto Over Explicit Type Declarations (5/9)

- Prevents “type mismatches”

```
std::map<std::string,int> m { {"tagged",6}, {"a",1}, {"this",4} };

// insert lots more key/value pairs into m

// let's print all key/value pairs ...
for (std::pair<std::string,int> const& p : m) {
  std::cout << p.first << ' ' << p.second << '\n';
}
// there's a problem in the loop - do you see it?

// unintentional type mismatches can be autoed away!!!
for (auto const& p : m) {
  std::cout << p.first << ' ' << p.second << '\n';
}
// not only is the loop more efficient, it’s also easier to type!!!
```

Prefer auto Over Explicit Type Declarations (6/9)

- Necessary to represent types known only to compilers

```
// lam is lambda that returns true when x is even integer
auto lam = [](int x) -> bool { return x%2 == 0; };

bool flag = lam(33); // flag is false
```

Prefer auto Over Explicit Type Declarations (7/9)

- Necessary for deducing return type …

```
// return type depends on template type parameters ...
template <typename T1, typename T2>
??? sum(T1 t1, T2 t2) {
  return t1 + t2;
}

auto s1 = sum(1, 1.1);  // type of s1 must be double
auto s2 = sum(1.1, 1);  // type of s2 must be double
auto s3 = sum(1.f, 1);  // type of s3 must be float
auto s4 = sum(1UL, 2U); // type of s4 must be unsigned long
```

Prefer auto Over Explicit Type Declarations (8/9)

- C++14 permits use of auto to indicate function's return type should be deduced using template type deduction

```
// since C++14, return type deduced by
// template type deduction ...
template <typename T1, typename T2>
auto sum(T1 t1, T2 t2) {
  return t1 + t2;
}

auto s1 = sum(1, 1.1);  // type of s1 is double
auto s2 = sum(1.1, 1);  // type of s2 is double
auto s3 = sum(1.f, 1);  // type of s3 is float
auto s4 = sum(1UL, 2U); // type of s4 is unsigned long
```

Prefer `auto` Over Explicit Type Declarations (9/9)

- `auto` prevents uninitialized variables
- `auto` declarations are less verbose
- `auto` prevents “type shortcuts”
- `auto` prevents “type mismatches”
- `auto` necessary to represent types known only to compilers [closures or lambdas]
- `auto` necessary to deduce return type using template type deduction

`auto` Type Specifier: Summary

- `auto` type deduction is usually same as template type deduction, but `auto` type deduction assumes braced initializer represents `std::initializer_list` while template deduction doesn't
- `auto` in a function return type implies template type deduction, not `auto` type deduction

decltype Specifier

- auto avoids need to write out type of variable, but it doesn't allow use of type of that variable
- decltype allows us to express precise type of an expression or declaration

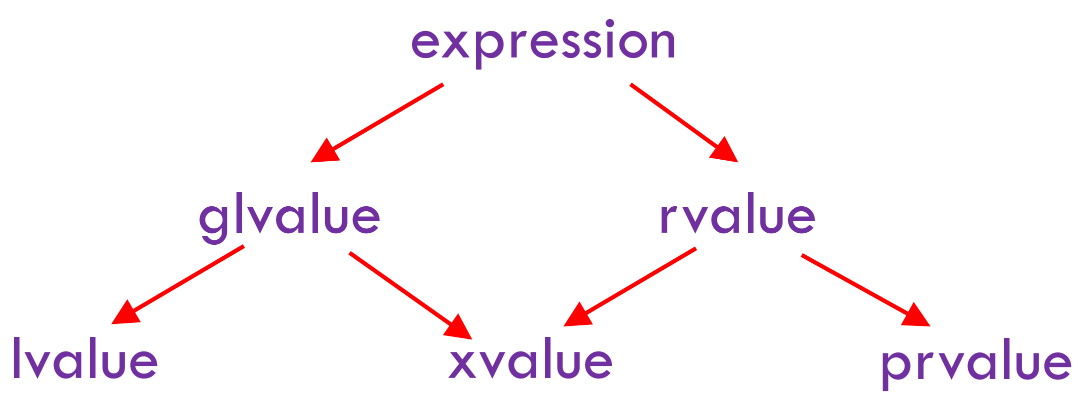
```
auto             i{0};

decltype(i)      j{i}; // j has type ???
decltype((i)) k{i}; // k has type ???
```

`decltype` Specifier: The Basics (1/5)

- If `e` is name of entity [variable, function, enumerator, class member] `decltype(e)` yields *declared type* of that entity
- Otherwise, if `e` is expression, `decltype(e)` produces type that reflects expression's *type and value category*
  - If `e` is *lvalue* of type `T`, `decltype(e)` produces `T&`
  - If `e` is *prvalue* of type `T`, `decltype(e)` produces `T`
  - If `e` is *xvalue* of type `T`, `decltype(e)` produces `T&&`

Value Categories Since C++11 (1/3)

- Every expression has a *type*
  - Describes static type of value that its computation produces
- Each expression also has *value category*
  - Describes how value was formed and affects how expression behaves



Value Categories Since C++11 (2/3)

- Examples of *lvalues* are:
  - Expressions that designate variables or functions
  - Applications of built-in indirection operator
  - Calls to function with return type that is lvalue reference
  - String literals

Value Categories Since C++11 (3/3)

- Examples of *prvalues* are:
  - Expressions that consist of literals [except string literals]
  - Applications of address operator, arithmetic, relational, logic operators
  - Calls to function with non-reference return type
  - Lambda expressions
- Examples of *xvalues* are:
  - Call to function with return type that is rvalue reference [such as `std::move`]
  - Cast to rvalue reference to object type

Here instead

decltype Specifier: The Basics (2/5)

- Given name or expression, decltype tells you type of name or expression [without evaluating expression]

```
auto i{0}, &ri{i}, *pi{&i};
auto const ci{0}, &cj{ci};

// what decltype tells you is exactly what you'd predict
decltype(i)     j{0};         // j has type ???int
decltype((i))Exp k{i};        // k has type ???lval to i
decltype(ri)    m{j};         // m has type ???
decltype(ci)    x{0};         // x has type ??? ro int
decltype(cj)    y{j};         // y has type ??? ref
decltype(ci+10) z{11};        // z has type ???
decltype(std::move(i)) n{12}; // n has type ???
decltype(cj)    xx(10);       // xx has type ???
decltype(ri+10) yy;           // yy has type ???
decltype(*pi)   zz{i};        // zz has type ???
```

decltype Specifier: The Basics (3/5)


```
// decltype parrots back exact type of name or expr you give it

int const i{};              // decltype(i) is int const

struct Point {
  int x, y;                 // decltype(Point::x) is int
};                          // decltype(Point::y) is int

Point p;                    // decltype(p) is Point
bool f(Point const& s);     // decltype(s) is Point const&
                            // decltype(f) is bool(Point const&)
if (f(p)) ...               // decltype(f(p)) is bool

std::vector<int> v;         // decltype(v) is std::vector<int>

if (v[0] == 0) ...          // decltype(v[0]) is int&
```

decltype Specifier: The Basics (4/5)

- decltype looks like a function and returns type of an expression

```
// ok: use template type deduction
template <typename T>
auto incr(T x) {
  return x+1;
}

// ok: x has type int
decltype(incr(10)) x {11};  // what is type of x???

// ok: y has type unsigned int
decltype(incr(10U)) y = 10; // what is type of y???
```

decltype Specifier: The Basics (5/5)


```
void g(std::string&& s) {
  // check the type of s:
  std::is_lvalue_reference<decltype(s)>::value;     // true or false
  std::is_rvalue_reference<decltype(s)>::value;     // true or false
  std::is_same<decltype(s), std::string&>::value;   // true or false
  std::is_same<decltype(s), std::string&&>::value; // true or false

  // check value category of s used as expression:
  std::is_lvalue_reference<decltype((s))>::value;     // true or false
  std::is_rvalue_reference<decltype((s))>::value;     // true or false
  std::is_same<decltype((s)), std::string&>::value;   // true or false
  std::is_same<decltype((s)), std::string&&>::value; // true or false
}
```

decltype Specifier: Deducing Function Return Types (1/3)

- Primary use of decltype in C++11 is declaring function templates where function's return type depends on its parameter types

```
// will this compile?
template <typename T1, typename T2>
decltype(x+y) Add(T1 x, T2 y) {
  return x+y;
}
```

`decltype` Specifier: Deducing Function Return Types (2/3)


```
// before C++14, it is only possible to let compiler
// determine return type by making function’s
// implementation part of its declaration ...
template <typename T1, typename T2>
auto Add(T1 x, T2 y) -> decltype(x+y) {
  return x+y;
}

int x = 10; double y = 20.2;
auto z = Add(x, y); // type of z ???

std::string sx = "hello"; char sy[]="world";
auto sz = Add(sx, sy); // type of sz ???
```

`decltype` Specifier: Deducing Function Return Types (3/3)

- `decltype` is important in places where explicit type is required

```
// how to get this code fragment to compile?
std::vector<int>    v1{1, 2, 3, 4};
std::vector<double> v2{1.1, 2.2, 3.3, 4.4, 5.5};
std::vector<???>    v3 = v1+v2;
// now v3 is {2.1, 4.2, 6.3, 8.4}
```

decltype Specifier: Deducing Function Return Types (4/5)

- Suppose we'd like to write function that takes container that supports indexing and returns *result of indexing operation*:

```
// std::vector<T>::op[] returns T&
// std::deque<T>::op[] returns T&
// unlike other containers,
// std::vector<bool>::op[] doesn't return bool&
template <typename Cont, typename Index>
auto access(Cont& c, Index i) {
  return c[i];
}
// incorrect since with auto return type,
// compilers employ template type deduction!!!
```

decltype Specifier: Deducing Function Return Types (5/5)

- decltype is required for correct definition:

```
// std::vector<T>::op[] returns T&
// std::deque<T>::op[] returns T&
// unlike other containers,
// std::vector<bool>::op[] doesn't return bool&
template <typename Cont, typename Index>
auto access(Cont& c, Index i) -> decltype(c[i]) {
  return c[i];
}
```

`decltype(auto)` Specifier (1/2)

- Since C++14, `decltype(auto)` specifier allows us to declare `auto` variables that have same type as with `decltype` type
  - `auto` specifies that type is to be deduced
  - `decltype` says that `decltype` rules should be used during the deduction

decltype(auto) Specifier (2/2)


```
int i {21};
int const &ri {i};

// auto type deduction
auto x = ri;             // x has type ???

// decltype type deduction
decltype(auto) y = ri; // y has type ???
```

```
std::vector<int> v {21};
auto xx = v[0];             // what is type of xx???
decltype(auto) yy = v[0]; // what is type of yy???
```

decltype(auto) Specifier: Deducing Function Return Types (1)


```cpp
// std::vector<T>::op[] returns T&
// std::deque<T>::op[] returns T&
// unlike other containers,
// std::vector<bool>::op[] doesn't return bool&
template <typename Cont, typename Index>
auto access(Cont& c, Index i) -> decltype(c[i]) {
  return c[i];
}
```

```cpp
// auto specifies that type is to be deduced
// decltype says decltype rules to be used
// during the deduction
template <typename Cont, typename Index>
decltype(auto) access(Cont& c, Index i) {
  return c[i];
}
```

`decltype(auto)` Specifier: Deducing Function Return Types (2)

- Want this to work for both *lvalues* and *rvalues*

```
// auto specifes that type is to be deduced
// decltype says decltype rules to be used
// during the deduction
template <typename Cont, typename Index>
decltype(auto) access(Cont& c, Index i) {
  return c[i];
}
```

```
template <typename Cont, typename Index>
decltype(auto) access(Cont&& c, Index i) {
  return std::forward<Cont>(c)[i];
}
```

decltype Specifier: Edge Case

- Something to worry about since C++14:

```
decltype(auto) f1() {
  int x = 0;
  return x;
}

decltype(auto) f2() {
  int x = 0;
  return ((x));
}
```

`decltype` Specifier: Summary

- `decltype` almost always yields type of variable or expression without any modifications
- For lvalue expressions of type `T` other than names, `decltype` always reports type of `T&`
- Since C++14, `decltype(auto)` deduces type from its initializer, but it performs type deduction using `decltype` rules

Structure Binding: The Basics (1/7)

- Uses type deduction to initialize multiple entities with elements or members of object
- Think of it as a *decomposition declaration*

```
struct S {
  int id;
  std::string name;
};
```

```
S s {1, "tv"};

// you can bind members of s directly to new names:
auto [u, v] {s};
// u and v are called structured bindings

S s1 {2, "ipad"};
auto [u1, v1] = S{2, "ipad"};
std::cout << u1 << " | " << v1 << "\n";
```

Structure Binding: The Basics (2/7)

- Especially useful for functions that return structures
  - Benefit is direct access and readability

```
struct S {
  int id;
  std::string name;
};
```

```
S getS(int id, std::string const& n) {
  return S{id, n};
}

// you can assign result directly to local names:
auto [i, n] {getS(1, "tv")};

// i & n are aliases for members id & name of returned structure
// with corresponding types and can be used as two
// different objects ...
if (i > 2) ...
n[0] = 'T';
```

Structure Binding: The Basics (3/7)

- Arrays can initialize a structured binding

```
double pt[3];
auto& [x, y, z] = pt;
x = 3; y = 4; z = 5;

// unsurprisingly, bracketed initializers are just shorthand for
// the corresponding elements of unnamed array elements

// Note: array size must equal number of bracketed initializers!!!
```

Structure Binding: The Basics (4/7)

- Useful for functions that return arrays

```
auto f() -> int(&)[2]; // what does this declaration mean?

auto [x, y] {f()};
// something unusual is happening here!!!
// evaluated as: auto e = f();
// array e is copied from initializer e, element-by-element
// finally, x and y become aliases for expressions e[0] and e[1]

auto& [u, v] = f();
// doesn't involve array copying
// instead usual rules for auto are followed: auto& e = f();
// x and y become aliases for expressions e[0] and e[1], resp
```

Structure Binding: The Basics (5/7)


```
std::array<int,4> get_a4();

// a,b,c,d are bindings to elements of array returned by getA4()
auto [a,b,c,d] = get_a4();

std::array<int,4> a4 {21, 22, 23, 24};
auto [e,f,g,h] = a4;
++e; // ok: modifies copy of a4[0]

auto& [i,j,k,l] = a4;
++i; // ok: modifies a4[0]

const auto& [m,n,o,p] = a4;
++i; // error: reference to constant object

// does this compile?
auto&& [q,r,s,t] = a4;
++q; // ok: modifies a4[0]
```

Structure Binding: The Basics (6/7)


```
std::set<int> s {-10, 10, -20, 20, 30, -30};

// would like to know if 10 is already inserted
std::pair<std::set<int>::iterator, bool> isi = s.insert(10);
if (isi.first) ...

auto is_inserted = s.insert(10);
std::set<int>::iterator it = is_inserted.first;
bool inserted = is_inserted.second;

// std::tie will unpack pair into local variables ...
std::tie(it, inserted) = s.insert(10);
if (inserted) ...

auto [it3, inserted3] = s.insert(10);
if (inserted3) ...
```

Structure Binding: The Basics (7/7)


```
std::map<std::string, int> mcp {
  { "Beijing",  21'707'000 }, {"Toronto", 6'508'123 },
  { "Tokyo",    9'273'000 },  { "London", 8'787'892 },
  { "New York", 8'622'698 },  { "Rio de Janeiro", 6'520'000 }
};

for (std::pair<const std::string, int>& kv : mcp) {
  ++kv.second;
}

for (auto& kv : mcp) {
  ++kv.second;
}

for (auto const& [city, population] : mcp) {
  std::cout << "<" << city << ", " << population << ">\n";
}
```

The tuple Type: The Basics (1)

- Heterogeneous list of elements whose types are specified or deduced at compile time

```
// create a four-element tuple
// elements are intialized with default value
std::tuple<std::string,int,int,std::complex<double>> t;

// create and initialize a tuple explicitly
std::tuple<int,double,std::string> t2{31, 3.14, "hlp3"};

// create tuple with make_tuple
auto t3 = std::make_tuple(32, 31.4, "hlp4");

// comparison and assignment ...
if (t2 < t3) { // compare value by value
  t2 = t3; // ok: assigns value for value
}
```

The tuple Type: The Basics (2)

- Elements accessed thro' get<>

```
std::tuple<int,double,std::string> t2{31, 3.14, "hlp3"};
auto t3 = std::make_tuple(32, 31.4, "hlp4");

// "iterate" over elements
std::cout << std::get<0>(t2) << '\n';
std::cout << std::get<1>(t2) << '\n';
std::cout << std::get<2>(t2) << '\n';

int i{1};
std::cout << std::get<i>(t2) << '\n'; // error

// access tuple using type
double d {std::get<double>(t2)};
// assign first value in t2 to t3
std::get<int>(t3) = std::get<int>(t2);
```