Support for Embedded Programming in C++11 and C++14

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Features New in C++11 (Incomplete List)

`auto`	`explicit` conversion functions	`alias templates`
range-based `for`	`override`, `final`	move semantics
scoped enums	underlying type for enums	`static_assert`
smart pointers	`make_shared`, `allocate_shared`	variadic templates
lambda expressions	enhanced `const_iterator` support	`std::bind`
type traits	numeric⇆`string` conversions	tuples
alignment control	`>>` as nested template closer	regular expressions
user-defined literals	default member initializers	singly-linked lists
hash tables	support for emplacement	new algorithms
perfect forwarding	support for concurrency	`enable_if`
`constexpr`	support for Unicode	rvalue references
raw string literals	uniform (braced) initialization	universal references
`std::array`	inherited & delegated constructors	`nullptr`
`initializer_list`	`std::function`	defaulted functions
`decltype`	trailing return types	deleted functions

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Features New in C++14 (Incomplete List)

Generalized function return type deduction	`make_unique`
Generic lambdas	Non-member `cbegin`, `cend`, `rbegin`, `rend`, `crbegin`, `crend`
Lambda init capture	Literal suffixes for `string`, `<chrono>` units, complex numbers
Relaxed rules for `constexpr` functions	Readers-Writer locks
Binary literals	IO support for quoted strings
Single quote as digit separator	Type-based `tuple` access
Variable templates	Aliases for transformation traits
Global operator delete with size parameter	Simplified operator functor templates
`[[deprecated]]` attribute	

C++11 and C++14 Features

Most as useful for embedded as for non-embedded development.

Covering—even *mentioning*—everything not possible.

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Agenda

- `auto`
- Enhanced enums (if time allows)
- Alignment control (in Bartek Szurgot's talk)
- `constexpr`

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Slide 5

auto

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Slide 6

Prefer `auto` to Explicit Type Declarations

Given

```
Widget w = expression of type Widget;
auto w = expression of type Widget;
```

why prefer `auto`?

Prefer `auto` to Explicit Type Declarations

Mandatory initialization:

```
int sum;                // possibly uninitialized
auto sum;               // error! no initializer from which
                        // to deduce type
auto sum = 0;           // fine, sum is int initialized to 0
```


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Prefer auto to Explicit Type Declarations

Typically less verbose; avoids syntactic noise:

```
std::vector<std::string::iterator> vsi;
…
for (std::string::iterator si : vsi) …        // explicit type
for (auto si : vsi) …                         // auto

template<typename It>
void someAlgorithm(It b, It e)
{
  typename std::iterator_traits<It>::value_type   // explicit
    firstElem = *b;                               // type
  auto firstElem = *b;                            // auto
  …
}
```


Prefer auto to Explicit Type Declarations

Avoids "type shortcut"-related problems.

```
std::vector<int> v;
…
unsigned sz = v.size();     // type "shortcut"!
                            // (should be
                            // std::vector<int>::size_type)
```

- Fine on 32-bit Windows.
  - ➡ `unsigned` and `std::vector<int>::size_type` are 32 bits.
- Unreliable on 64-bit Windows.
  - ➡ `unsigned` is 32 bits, `std::vector<int>::size_type` is 64 bits.

```
auto sz = v.size();         // sz is std::vector<int>::size_type
```

Example due to Andrey Karpov.

Prefer auto to Explicit Type Declarations

Avoids accidental temporary creation:

```
std::map<std::string, int> m;    // holds objects of type
                                 // std::pair<const std::string,
                                 //           int>
…
for (const std::pair<std::string, int>& p : m) …
                                 // creates temp on
                                 // each iteration ⇒
                                 // std::string is copied
for (const auto& p : m) …        // no temps created
```

Example due to Stephan T. Lavavej.

Prefer auto to Explicit Type Declarations

Most efficient way to store function objects:

```
std::function<int(int)> f1a =                // closure could
  [a,b](int x) { return x*x - a/10 + b; };   // be on heap


auto f1b =                                   // closure not on
  [a,b](int x) { return x*x - a/10 + b; };   // heap
```

Prefer `auto` to Explicit Type Declarations

Efficiency difference not limited to closures:

```
inline void f(int x, int y, int z) { … }

std::function<void()> f2a =       // func. obj. from std::bind
  std::bind(f, a, b, c);          // could be on heap

auto f2b = std::bind(f, a, b, c); // func. obj. from std::bind
                                  // not on heap
```


`auto` and Code Clarity

`auto` a tool, not an obligation.

- If explicit type clearer, use it.

But:

- IDEs may show types of `auto`-declared variables.
  - ➧ E.g. Visual Studio 2010+.
- Much success in other languages with similar features.

auto

?

constexpr

Use `constexpr` Whenever Possible

Two meanings:

- **Objects**: `const` + value known during compilation.
- **Functions**: ≈ return `constexpr` result if called with `constexpr` args.
  - ➡ Truth a bit more subtle.

`constexpr` Objects

Must be initialized with value known during compilation:

```
constexpr std::size_t arraySize;     // error! no initializer
int sz;                              // non-constexpr variable
…
constexpr auto arraySize1 = sz;      // error! sz's value not
                                     // known at compilation
constexpr auto arraySize2 = 10;      // okay
```

Usable in contexts requiring compile-time constants:

```
std::array<int, sz> data1;           // error! sz's value still
                                     // unknown at compilation
std::array<int, arraySize2> data2;   // fine, arraySize2
                                     // is constexpr
```

`const` (hence unmodifiable):

```
arraySize2 = 100;                    // error!
```

`constexpr` Objects vs. `const` Objects

`const` objects may be initialized at runtime:

```
int sz;                                 // as before

…

const auto arraySize3 = sz;             // fine, arraySize3 is
                                        // const copy of sz
```

Such objects invalid in contexts requiring compile-time values:

```
std::array<int, arraySize3> data3;      // error! arraySize3
                                        // isn't constexpr
```

All `constexpr` objects are `const`, but not all `const` objects are `constexpr`.

`constexpr` Objects vs. `const` Objects

Bottom line:

- Need compile-time value ⇒ `constexpr` is proper tool.
- When `constexpr` viable, use it.
  - ➧ Resulting object usable in more contexts.

```
const int maxVal = 100;             // typically inferior
constexpr int maxVal = 100;         // typically superior
```


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`constexpr` Functions

Quite different from `const` functions.

- Not limited to member functions.
- "Execute" during compilation and return `constexpr` results if :
  - ➡ Arguments are `constexpr`.
  - ➡ Result used in `constexpr` context.
- *May* (but *may not*) "execute" during compilation if:
  - ➡ Arguments are `constexpr`.
  - ➡ Result *not* used in `constexpr` context.
- Execute at runtime for ≥1 non-`constexpr` argument.
  - ➡ No need to "overload" on `constexpr`.
    - ◆ `constexpr` functions take `constexpr` *and* non-`constexpr` args.

Note:

- `constexpr` functions may not return `const` results.
- `constexpr` functions may not "execute" during compilation.

`constexpr` Functions

Consider an experiment where:

- 3 possible lighting levels: high, low, off.
- 3 possible fan speeds: high, low, off.
- 3 possible temperature values: high, medium, low.
- Etc.

n independent 3-valued conditions ⇒ 3^n combinations.

Holding all results in a `std::array` ⇒ compute 3^n during compilation.

- Goal: calculate with `constexpr` function.

constexpr Functions

Client view:

```
constexpr int pow(int base, int exp) noexcept   // constexpr
{                                                // function
  ...                                            // coming soon
}
constexpr auto numConds = 5;
std::array<int, pow(3, numConds)> results;     // fine, results
                                                // has 3^numConds
                                                // elements
```

Note:

- `pow` called with `constexpr` values in a `constexpr` context.
  - ➡ Guarantees compile-time evaluation.

constexpr Functions

`pow` also callable at runtime:

```
auto base = readFromDB("base");          // runtime call
auto exp = readFromDB("exponent");       // runtime call
auto baseToExp = pow(base, exp);         // runtime call
```


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`constexpr` Functions

`constexpr` functions are constrained.

- May take and return only *literal types*.
  - ➧ Essentially types where values compile-time-computable.
- Implementations restricted.
  - ➧ Restrictions differ for C++11 and C++14.

In C++11, exactly one executable statement: `return`.

- But `?:` emulates `if`/`else` and recursion emulates iteration, so:

```
constexpr int pow(int base, int exp) noexcept
{
  return (exp == 0 ? 1 : base * pow(base, exp - 1));
}
```


`constexpr` Functions

C++14 restrictions much looser.

- Multiple statements okay
- Local variables of literal type okay.
- Iteration statements okay.
- Etc.

Hence:

```
constexpr int pow(int base, int exp) noexcept          // C++14
{                                                      // only
  auto result = 1;
  for (int i = 0; i < exp; ++i) result *= base;

  return result;
}
```

Literal UDTs

Literal types can be user-defined!

- `constexpr` constructors and other member functions.

```
class Point {
public:
  constexpr Point(double xVal = 0, double yVal = 0) noexcept
  : x(xVal), y(yVal)
  {}

  constexpr double xValue() const noexcept { return x; }
  constexpr double yValue() const noexcept { return y; }

  void setX(double newX) noexcept { x = newX; }
  void setY(double newY) noexcept { y = newY; }

private:
  double x, y;
};

constexpr Point p1(9.4, 27.7);         // fine

constexpr Point p2(28.8, 5.3);         // also fine
```


Literal UDTs

Given

```
constexpr
Point midpoint(const Point& p1, const Point& p2) noexcept
{
  return { (p1.xValue() + p2.xValue()) / 2,   // call constexpr
           (p1.yValue() + p2.yValue()) / 2 }; // member funcs
}
```

a `constexpr Point` object could be defined as follows:

```
constexpr auto mid = midpoint(p1, p2);     // init constexpr
                                           // object w/result of
                                           // constexpr function
```

Literal UDTs

In C++14, even setters can be `constexpr`:

```
class Point {
public:
  ...
  constexpr void setX(double newX) noexcept       // C++14 only
  { x = newX; }

  constexpr void setY(double newY) noexcept       // C++14 only
  { y = newY; }
  ...
};
```


Literal UDTs

Hence:

```
// return reflection of p with respect to the origin
constexpr Point reflection(const Point& p) noexcept
{
  Point result;                   // create non-const Point

  result.setX(-p.xValue());       // set its x and y values
  result.setY(-p.yValue());

  return result;                  // return constexpr copy of it
}

constexpr Point p1(9.4, 27.7);          // as before
constexpr Point p2(28.8, 5.3);

constexpr auto mid = midpoint(p1, p2);  // as before

constexpr auto reflectedMid =           // reflectedMid's value
  reflection(mid);                      // is (-19.1 -16.5) and
                                        // a compile-time
                                        // constant
```

`constexpr` Pros and Cons

Pros:

- Can shift runtime work to compile time.
  - ➧ May help move objects from RAM to ROM.
- `constexpr` begets `constexpr`.
  - ➧ `constexpr` objects/functions facilitate creation of more `constexpr` objects/functions.

Con:

- `constexpr` is interface.
  - ➧ Removing `constexpr` can break arbitrary amounts of code.
  - ➧ Use `constexpr` only if you're willing to commit to it.

`constexpr`

Enhanced enums

Prefer Scoped enums to Unscoped enums

Unscoped ("old") enums have several weaknesses:

```
enum Color { red, green, blue };
```

- **Namespace pollution**: `red`, `green`, `blue` in scope containing `enum`.

```
enum Color { red, green, blue };
void blue();                        // error!
```

- **Unspecified size**: `sizeof(Color)` up to implementation.
- **Declaration-only not allowed**: definition must be given.

```
enum Options;                       // error!
```

Prefer Scoped enums to Unscoped enums

- **Weak typing**: enumerators implicitly convert to `int`.

```
enum Color { red, green, blue };
Color c;
…
double d = c;              // Color→int→double
if (c) …                   // Color→int→bool
enum Options { debug, optimize, log };
Options opt;
…
if (c == opt) …            // compare Color and Options!
```


Scoped enums

Scoped enums ("enum classes") address all these issues:

```
enum class Color;                          // fine
enum class Color { red, green, blue };
void blue();                               // fine
Color c;
…
double d = c;                              // error!
if (c) …                                   // error!
enum class Options { debug, optimize, log };
Options opt;
…
if (c == opt) …                            // error!
```

Underlying Type

Default underlying type for scoped enums is `int`:

```
enum class Color { red, green, blue };   // in binary code,
                                         // red, green, blue
                                         // are ints
```

Can be overridden:

```
enum class Color: std::uint64_t          // in binary code,
{ red, green, blue };                    // red, green, blue
                                         // are std::uint64_ts
```


Underlying Type

Can now be specified for unscoped enums, too:

```
enum Options: std::uint8_t { debug, optimize, log };
```

Such enums may also be forward-declared:

```
enum Options: std::uint8_t;              // forward declaration
void doWork(std::function<void()> f,
            Options opts);               // fine
```

But other issues remain:

- Namespace pollution
- Weak typing

enums, `std::tuple`, and `std::get`

Use of scoped enums with `std::get` verbose:

```
using StackOverflowData =
  std::tuple<std::string,                              // name
             std::size_t, std::size_t, std::size_t,    // badges
             std::size_t>;                             // reputation

enum class SOIndices {
  name, bronzeCount, silverCount, goldCount, rep
};

void processSOUser(const StackOverflowData& user)
{
  auto badgeCount =
    std::get<std::size_t(SOIndices::bronzeCount)>(user) +
    std::get<std::size_t(SOIndices::silverCount)>(user) +
    std::get<std::size_t(SOIndices::goldCount)>(user);

  …
}
```

Even worse with `static_cast`s…

enums, `std::tuple`, and `std::get`

Enum→`int` conversion makes use of unscoped enums simpler:

```
enum {                                                 // not
  name, bronzeCount, silverCount, goldCount, rep       // enum
};                                                     // class

…
void processSOUser(const StackOverflowData& user)
{
  auto badgeCount = std::get<bronzeCount>(user) +
                    std::get<silverCount>(user) +
                    std::get<goldCount>(user);

  …
}
```

Casting to Underlying Type

Verbosity of scoped enum approach can be reduced a bit:

```
// cast enumerator to underlying type
template<typename E>
constexpr typename std::underlying_type<E>::type
  toUType(E enumerator)
{
  return
    static_cast<typename
                  std::underlying_type<E>::type>(enumerator);
}

void processSOUser(const StackOverflowData& user)
{
  auto badgeCount =
    std::get<toUType(SOIndices::bronzeCount)>(user) +
    std::get<toUType(SOIndices::silverCount)>(user) +
    std::get<toUType(SOIndices::goldCount)>(user);
  …
}
```

`toUType` also more general than having clients cast to `std::size_t`:

- Not all enum-integral conversions call for `std::size_t`s.

Casting to Underlying Type

Alias template can hide "`template blah_blah_blah::type`" syntax:

```
template<typename E>                          // from previous slide
constexpr
typename std::underlying_type<E>::type toUType(E enumerator)
{
  return
    static_cast<typename
                  std::underlying_type<E>::type>(enumerator);
}


template<typename E>                                  // alias
using UnderlyingType =                                // template
  typename std::underlying_type<E>::type;

template<typename E>                                  // revised
constexpr UnderlyingType<E> toUType(E enumerator)     // toUType
{
   return static_cast<UnderlyingType<E>>(enumerator);
}
```

Casting to Underlying Type

C++14's `auto` return type eliminates type repetition.

- Without alias template:

```
template<typename E>
constexpr auto toUType(E enumerator)                    // C++14
{
  return
    static_cast<typename
                  std::underlying_type<E>::type>(enumerator);
}
```

- With alias template:

```
template<typename E>
using UnderlyingType = typename std::underlying_type<E>::type;

template<typename E>
constexpr auto toUType(E enumerator)                     // C++14
{
  return static_cast<UnderlyingType<E>>(enumerator);
}
```


Enhanced enums

Further Information

Further Information

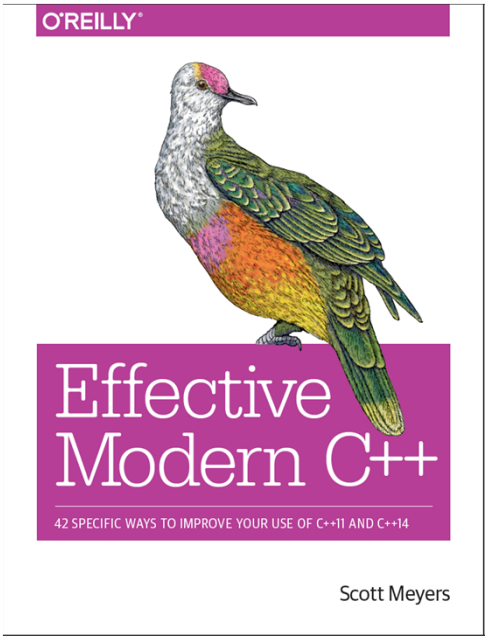
C++11 and C++14 in embedded systems:

- "Embedded Programming with C++11," Rainer Grimm, *Meeting C++*, November 2013.
  - ➧ Overviews prevention of narrowing conversions, `static_assert`, user-defined literals, `constexpr`, generalized PODs, `std::array`, move semantics, perfect forwarding, and smart pointers.
- "C++14 Adds Embedded Features," William Wong, *electronic design*, 19 August 2014.
  - ➧ Brief coverage of `auto` for lambda parameters and function return types, in-class aggregate initialization, user-defined literals, standard unit suffixes, `constexpr`, binary literals, and the digit separator.

Further Information

Effective use of C++11 and C++14:

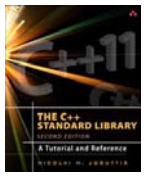
- *Effective Modern C++*, Scott Meyers, O'Reilly, 2015.
  - ➡ Due out any day now...



Further Information

C++11:

- *Programming Languages — C++*, Document 14882:2011, ISO/IEC, 2011-09-01.
  - ➡ ISO product page: http://tinyurl.com/5soe87 (CHF238 ≡ ~$245).
  - ➡ ANSI product page: http://tinyurl.com/8m6vb5m ($30).
  - ➡ First post-Standard draft (N3337): http://tinyurl.com/6wkboer (free).
    - ◆ Essentially identical to the standard.
- *C++11*, Wikipedia.
- *Overview of the New C++ (C++11/14)*, Scott Meyers, `http://www.artima.com/shop/overview_of_the_new_cpp`.
  - ➡ Annotated training materials (analogous to these).
- *The C++ Standard Library, Second Edition*, Nicolai M. Josuttis, Addison-Wesley, 2012.



Further Information

C++14:

- *Working Draft, Standard for Programming Language C++*, Document N3797, ISO/IEC, 2013-10-13.
  - ➧ Final freely available draft version of C++14.
- *C++14*, Wikipedia.
- "The view from C++ Standard meeting April 2013," Michael Wong, *C/C++ Cafe* (blog) :
  - ➧ Part 1, 25 April 2013. Discusses core language.
  - ➧ Part 2, 26 April 2013. Discusses standard library.
  - ➧ Part 3, 29 April 2013. Discusses concurrency and TSes.
- *Overview of the New C++ (C++11/14)*, Scott Meyers, `http://www.artima.com/shop/overview_of_the_new_cpp`.
  - ➧ Annotated training materials (analogous to these).

Further Information

`auto`:

- "C++11, VC++11, and Beyond," Herb Sutter, *Going Native 2012*, 3 February 2012.
  - ➧ Summarizes pros and cons of using `auto`.
- "In what way can C++0x standard help you eliminate 64-bit errors," Andrey Karpov, `viva64.com`, 28 February 2010.
  - ➧ Source of "type shortcut" example.
- "STL11: Magic && Secrets," Stephan T. Lavavej, *Going Native 2012*, 2 February 2012.
  - ➧ Source of accidental temporary example.
- "Inferring too much," Motti Lanzkron, *I will not buy this blog, it is scratched!*, 21 February 2011.

Further Information

`constexpr`:

- "Constexpr – Generalized Constant Expressions in C++11," Alex Allain, cprogramming.com.
- "Using constexpr to Improve Security, Performance, and Encapsulation in C++," Danny Kalev, *Software Quality Matters Blog*, 19 December 2012.
- "constexpr," Jarryd Beck, *The New C++* (blog), 14 November 2011.

Further Information

Enhanced enums:

- "Strongly typed enumerations," *Wikipedia,* http://tinyurl.com/7szjdey.
  - ➧ Subsection of entry for "C++11".
- "enum class -- scoped and strongly typed enums," Bjarne Stroustrup, http://tinyurl.com/2cvylcc.
  - ➧ Subsection of "C++11 – the recently approved new ISO C++ standard."
- "Closer to Perfection: Get to Know C++11 Scoped and Based Enum Types," Danny Kalev, *smartbear.com*, 6 February 2013.
- "Better types in C++11 - nullptr, enum classes (strongly typed enumerations) and cstdint," Alex Allain, CPrograming.com.

Further Information

Alias templates:

- "Handling dependent names," R. Martinho Fernandes, *Flaming Dangerzone*, 27 May 2012.

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