

C Advanced

A two day course for professional programmers

Agenda

2

Day 1: 0930-1530
Standard
Incomplete Types
Exercise and Lunch
Structs and Enums
Objects
Sequencing
Exercise

Day 2: 0930-1530
Representation
Lvalues
Arrays
Exercise and Lunch
Pointers
Conversions
Threading

C Advanced

3

Standard

- <http://www.open-std.org/jtc1/sc22/wg14>



Joint
Technical
Committee
1

Sub
Committee
22

Working
Group
14

John Wiley: ISBN 0470845732

- <http://www.knosof.co.uk/cbook/cbook.html>
 - ◆ commentary on every sentence in the c99 standard+
- Peter Norvig advises
 - ◆ get involved in a language standardization
 - ◆ get off the language standardization asap :-)

Clauses

5

- 3. Terms, definitions, and symbols**
- 4. Conformance**
- 5. Environment**
- 5.1.1.3 Diagnostics**
- 5.1.2.3 Program execution**
- 1. Language**
- 6.2 Concepts**
- 6.2.5 Types**
- 6.2.6 Representations of types**
- 6.3 Conversions**
- 6.3.2.1 Lvalues, arrays, and function designators**
- 6.5 Expressions**
- 6.7 Declarations**
- 6.8 Statements and blocks**



These are the main clauses we will be looking at

- 6
 - **trust the programmer**
 - ◆ let them do what needs to be done
 - ◆ the programmer is in charge not the compiler
 - **keep the language small and simple**
 - ◆ provide only one way to do an operation
 - ◆ new inventions are not entertained
 - **make it fast, even if its not portable**
 - ◆ target efficient code generation
 - ◆ int promotion rules
 - ◆ sequence points
 - **rich expressions**
 - ◆ lots of operators
 - ◆ expressions combine into larger expressions



3.12 implementation

particular set of software, running in a particular translation environment under particular control options, that performs translation of programs for, and supports executions of functions in, a particular execution environment.

1. Environment

para 1 - An implementation translates C source files and executes C programs in two data-processing system environments, which will be called the translation environment and the execution environment...



Implementation means compiler/translator

3.4 behavior external appearance or action

***3.4.1 implementation-defined behavior
unspecified behavior where each implementation
documents how the choice is made.***

***3.4.3 undefined behavior
behavior, upon use of a nonportable or erroneous
program construct or of erroneous data, for which
this International Standard imposes no requirement.***

***3.4.4 unspecified behavior
use of an unspecified value, or other behavior where
this International Standard provides two or more
possibilities and impose no further requirements on
which is chosen in any instance.***

- behavior in Java/C# is completely defined
- a lot of behavior in C is not - why not?

question

3.4 behavior

...

3.4.1 implementation-defined behavior

...

3.4.3 undefined behavior

...

3.4.4 unspecified behavior

...



3.8 constraint

restriction, either syntactic or semantic, by which the exposition of language elements is to be interpreted.

3.10 diagnostic message

message belonging to an implementation-defined subset of the implementation's message output.

5.1.1.3 Diagnostics

para 1 - A conforming implementation shall produce at least one diagnostic message ... if a ... translation unit contains a violation of any syntax rule or constraint ...

Diagnostic messages need not be produced in other circumstances.

- an implementation is required to produce a diagnostic message for a syntax violation*

6.5.16 Assignment operators

Syntax

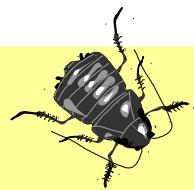
assignment-operator:

= *= /= %= += -= <<= >>= &= ^= |=

diagnostics

syntax.c

```
int x = 0;  
x := 42;
```



>gcc syntax.c

→ error: expected expression before '=' token

*if it is the first violation

- an implementation is required to produce a diagnostic message for a constraint violation*

6.5.16 Assignment operators

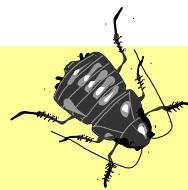
Constraints

As assignment operator shall have a modifiable lvalue as its left operand.



constraints.c

```
const int x = 0;  
x = 42;
```



>gcc constraints.c

→ error: assignment of read-only variable 'x'

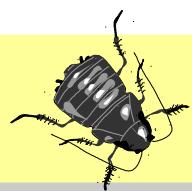
- an implementation is not required to produce a diagnostic message for any other violation!

5.1.2.3 Program execution

para 2 – At certain specified points in the execution sequence called sequence points, all side effects of previous evaluations shall be complete and no side effects of subsequent evaluations shall have taken place.

semantics.c

```
int x = 0;  
x = x++;
```



```
>gcc semantics.c  
→ ...no diagnostic...
```

```
>gcc -Wall semantics.c  
→ warning: operation on 'x' may be undefined
```

4. Conformance

para 1 - ... "shall" is to be interpreted as a requirement on an implementation or on a program; conversely, "shall not" is to be interpreted as a prohibition.

para 2 - If a "shall" or "shall not" requirement that appears outside of a constraint is violated, the behavior is undefined. Undefined behavior is otherwise indicated in this International Standard by the words "undefined behavior", or by the omission of any explicit definition of behavior. There is no difference in emphasis among these three; they all describe "behavior that is undefined"



Annex J.2 lists 190+ undefined behaviors.

4. Conformance

para 5 - A strictly conforming program shall use only those features of the language and library specified in this International Standard.

It shall not produce output dependent on any unspecified, undefined, or implementation-defined behavior and shall not exceed any minimum implementation limit.

para 6 - A conforming ... implementation shall accept any strictly conforming program.

para 7 - A conforming program is one that is acceptable to a conforming implementation.



The standard never writes about "correct" programs.
The only proper terms are conformance/conforming.

- **3. Terms, definitions, and symbols**
 - ◆ **3.1 access**

Execution time action to read or modify the value of an object.

NOTE 1: where only one of these two actions is meant, "read" or "modify" is used.

NOTE 2: "Modify" includes the case where the new value being stored in the same as the previous value.

NOTE 3: Expressions that are not evaluated do not access objects.

What use is an expression that is not evaluated?



- **3. Terms, definitions, and symbols**
 - ◆ **3.15 object**

*A region of data storage in the execution environment,
the contents of which can represent values*



What C calls objects, other languages call variables.



An object's representation is held in a contiguous sequence of bytes.



An object is addressable.

- **3. Terms, definitions, and symbols**
 - ◆ **3.15 object**

NOTE: when referenced, an object may be interpreted as having a particular type.



A reference that does not interpret the contents of an object, for example as an argument to `memcpy`, does not need to interpret it as having a particular type.



Objects have storage duration but no linkage.
Identifiers have linkage but no storage duration.
Constants have only a value.

- 3. Terms, definitions, and symbols
 - ◆ 3.6 byte

Addressable unit of data storage large enough to hold any member of the basic character set of the execution environment

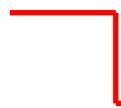


Each byte is at least 8 bits wide.
A char, whether signed or unsigned, occupies exactly one byte.

bytes



An implementation cannot hide the internal bits of an object.



Why not?



- **3. Terms, definitions, and symbols**
 - ◆ **3.19 value**

Precise meaning of the contents of an object when interpreted as having a specific type.



A literal also has a value. Its type is determined by both the lexical form of the token and its numeric value.

• 6. Language

◆ 6.2 Concepts

■ 6.2.5 Types

*para 1 - The meaning of a value stored in an object or returned by a **function** is determined by the type of the expression used to access it.*

para 1 – Types are partitioned into

- object types (*types that describe objects*)
- function types (*types that describe functions*), and
- *At various points within a translation unit an object may be incomplete (lacking sufficient information to determine the size of objects of that type) or complete (having sufficient information).*

types



C has a relatively weak type system. C++ added much greater support for "typing".

- 6. Language
 - ◆ 6.5 Expressions

para 1 - An expression is a sequence of operators and operands that ...

- *specifies computation of a value, or*
- *that designates an object or a function, or*
- *that generates side effects, or*
- *that performs a combination thereof.*

- rich expressions
 - ◆ lots of operators
 - ◆ expressions combine into larger expressions



- 5. Environment
 - ◆ 5.1 Conceptual models
 - 5.1.2 Execution environment
 - 5.1.2.3 Program execution

para 2 –

- Accessing a volatile object,
- modifying an object,
- modifying a file,
- or calling a function that does any of those operations are all side effects which are changes in the state of the execution environment.

- 5. Environment
 - ◆ 5.1 Conceptual models
 - 5.1.2 Execution environment
 - 5.1.2.3 Program execution

para 3 – The presence of a sequence point between the evaluation of expressions A and B implies that every value computation and side effect associated with A is sequenced-before every value computation and side effect associated with B. (A summary of sequence points is given in annex C.)

Why do so few expressions cause a sequence point?



- 5. Environment
 - ◆ 5.1 Conceptual models
 - 5.1.2 Execution environment
 - 5.1.2.3 Program execution

*para 3 – In the abstract machine, all expressions are evaluated **as** specified by the semantics.*
*An actual implementation need not evaluate part of an expression **if** it can deduce that its value is not used and that no needed side effects are produced (including any caused by calling a function or accessing a volatile object).*

as-if

Why does the as-if rule exist?



contents

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- **Spirit of C**
- **Main clauses**
- **Behavior**
- **Diagnostics**
- **Conformance**
- **Key terms**
- **Types**
- **Expressions**
- **Program execution**

Incomplete Types

- 6.2.5 Types
 - ◆ para 1 - Types are partitioned into
 - object types (types that describe objects),
 - function types (types that describe functions),
 - At various points within a translation unit an object may be incomplete (lacking sufficient information to determine the size of objects of that type) or complete (having sufficient information).
- 6.2.5 Types
 - ◆ para 19 – The void type ... is an incomplete type that cannot be completed.
 - ◆ para 22 – An array of unknown size is an incomplete type.
 - ◆ para 22 – A structure or union type of unknown content is an incomplete type.

• 6.7.6.3 Function declarators

- ♦ para 14 – An empty list in a function declarator that is part of a definition of that function specifies that the function has no parameters.

```
int f(void) { ... }  
int f() { ... }
```

equivalent



- ♦ para 14 – The empty list in a function declarator that is not part of a definition of that function specifies that no information about the number or types of the parameters is supplied.

```
int f(void);  
int f();
```

not equivalent



- when do you get a diagnostic?
 - ◊ gcc clo.c
 - ◊ gcc -Wall clo.c
 - ◊ gcc -Wmissing-prototypes clo.c

```
int f();  
  
int main(void)  
{  
    return f(4, 2);  
}  
  
int f(int value)  
{  
    return value;  
}
```

clo.c



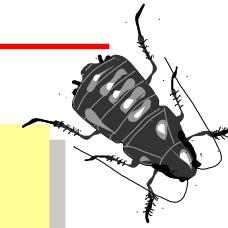
- when do you get a diagnostic?
 - ◊ gcc clo.c → NO
 - ◊ gcc -Wall clo.c → NO! why not?
 - ◊ gcc -Wmissing-prototypes clo.c → YES

answer-1



```
int f();  
  
int main(void)  
{  
    return f(4, 2);  
}  
  
int f(int value)  
{  
    return value;  
}
```

clo.c



exercise-2

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- why do you still get a diagnostic? _____

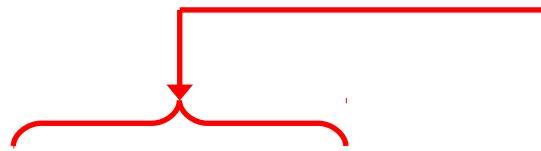
◆ gcc -Wmissing-prototypes clo.c

→ warning: no previous prototype for 'f'

```
int f(int value)
{
    return value;
}

int main(void)
{
    return f(42);
}
```

clo.c



- because f() is not declared with external linkage and there is no previous function declaration
 - option : if f() is not used in another source file then define it with internal linkage

answer-2a

```
static int f(int value)
{
    return value;
}

int main(void)
{
    return f(42);
}
```

clo.c

- because f() is not declared with external linkage and there is no previous function declaration
 - option : if f() is used in another source file then declare it in a header and define it with external linkage

```
int f(int value);
```

clo.h

```
#include "clo.h"

int f(int value)
{
    return value;
}

int main(void)
{
    return f(42);
}
```

clo.c

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6.2.5 Types

- para 22 – An array of unknown size is an incomplete type.

incomplete arrays



```
int a1[42];  
extern int a2[42];  
typedef int a3[42];
```

these are
object types



```
int a1[];  
extern int a2[];  
typedef int a3[];
```

these are
incomplete

unknown size

- are these fragments conforming or not?

```
struct wibble;
```

```
        struct wibble w1[42];
extern struct wibble w2[42]; ←
typedef struct wibble w3[42];
```

```
        struct wibble w1[];
extern struct wibble w2[];
typedef struct wibble w3[];
```



- neither are conforming!

```
struct wibble;
```

```
        struct wibble w1[42];  
extern struct wibble w2[42];  
typedef struct wibble w3[42];
```



```
        struct wibble w1[];  
extern struct wibble w2[];  
typedef struct wibble w3[];
```



answer



Incomplete arrays can be incomplete in their size
but not in their element type



- 6.7.6.2 Array declarators
 - ◊ para 1 – the element type shall not be an incomplete type
- are these fragments conforming or not?

```
struct wibble;  
  
struct wibble x[4];  
  
struct wibble x[];  
  
struct wibble * ptr;
```



```
struct wibble;
```

 struct wibble x[4];

 struct wibble x[] ;

 struct wibble * ptr;

- are these code fragments conforming?
- if not, why not?

exercise

```
int table[] =  
{  
    1, 2, 3,  
    4, 5, 6  
};
```

```
int table[][] =  
{  
    { 1, 2, 3 },  
    { 4, 5, 6 }  
};
```



answer



```
int table[] =  
{  
    1, 2, 3,  
    4, 5, 6  
};
```

this is conforming



```
int table[][] =  
{  
    { 1, 2, 3 },  
    { 4, 5, 6 }  
};
```

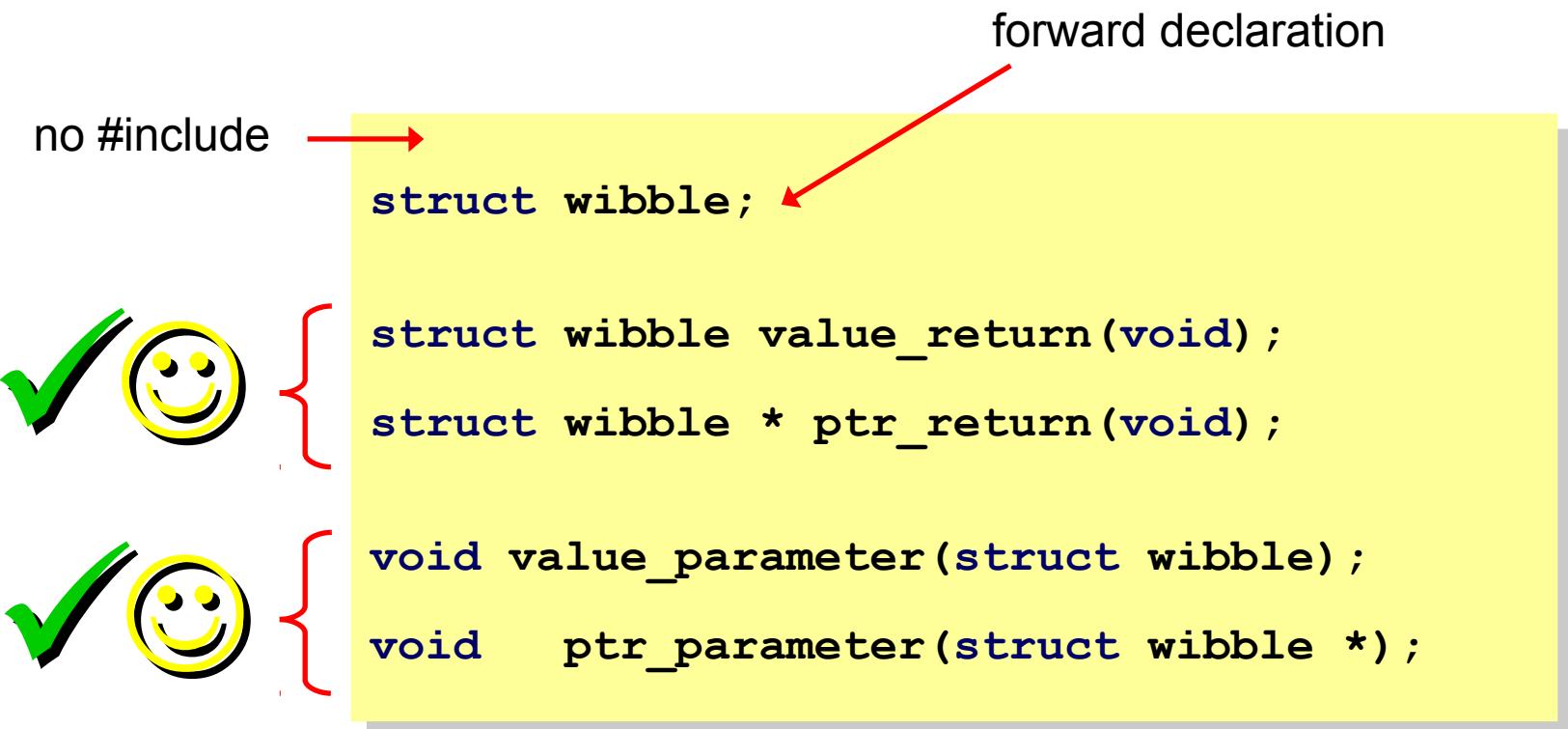
this is not conforming

function declarators

42

- 6.7.6.3 Function declarators

- ♦ para 12 - If the function declarator is not part of a definition of that function, parameters may have incomplete types...



forward declaration

no #include →

```
struct wibble;
struct wibble value_return(void);
struct wibble * ptr_return(void);

void value_parameter(struct wibble);
void     ptr_parameter(struct wibble *);
```

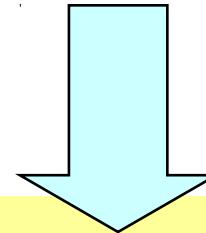
- manage dependencies aggressively
 - ◆ both physically and logically

dependencies



```
#include "wibble.h"

void many_includes(wibble * ptr);
void are_unnecessary(wibble value);
```



```
struct wibble;
```

```
void many_includes(struct wibble * ptr);
void are_unnecessary(struct wibble value);
```

Structs and Enums

- these are the two recommended styles
 - ◆ any deviation from these two is unhelpful

Diagram illustrating two recommended styles for defining a C struct:

- Style 1 (Top):** `typedef struct date` (tag name) `{` `...` `} date;` (typedef name)
- Style 2 (Bottom):** `struct date` (tag name) `{` `...` `};`

if you use a `typedef`
make the `typedef`
name the same as
the tag name.

or don't `typedef`.

- making the tag_name and the typedef name different creates a name difference when there is no actual type difference

```
struct date_tag  
{  
    ...  
};
```

```
typedef struct date_tag date; ?
```

```
struct date_tag deadline;  
...  
date delay = deadline;
```



- omit the tag name and `typedef`?
 - ◆ this forces a single syntax

```
typedef struct {  
    ...  
} date;
```



```
struct date_tag deadline;  
...  
date delay = deadline;
```



```
date deadline;  
...  
date delay = deadline;
```



- omit the tag name and don't `typedef`?
 - ◆ also changes the namespace
 - ◆ you can't use the type name as an object name

```
struct date
{
    ...
};
```

```
struct date date;
```



```
typedef struct
{
    ...
} date;
```

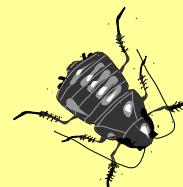
```
date date;
```



- omit the tag name?

- ◆ also prevents a bizarre bug
- ◆ struct X; means X does not have to already exist
- ◆ struct X; forces X to name a possibly new type!

```
struct date
{
    ...
};
```



```
void func(struct date_t *);
```



```
typedef struct {
    ...
} date;
```



- omit the tag name?
 - ◆ is not an option for cyclically dependent types

```
struct link
{
    struct link * next;
    ...
};
```



```
typedef struct link
{
    struct link * next;
} link;
```



variation-2

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- omit the tag name?
 - ◆ prevents forward declarations
 - ◆ forces unnecessary #includes

date.h

```
typedef struct {  
    ...  
} date;
```

use.h

```
#include "date.h"  
  
void f(date d);
```



- **writing a tag name?**

- ◆ allows forward declarations
- ◆ allows omission of unnecessary #includes



date.h

```
struct date
{
    ...
};
```

```
struct date;

void f(struct date d);
```

- these are the two recommended styles
 - ◆ any variation is unhelpful

```
tag name →  
typedef struct date  
{  
    ...  
} date;  
↑  
typedef name
```

if you use a `typedef`
make the `typedef`
name the same as
the tag name.

```
struct date  
{  
    ...  
};
```

or don't `typedef`.

typedef != definition

- a **typedef** does *not* create a new type
 - ◆ perhaps it should have been named **typedecl** ?

```
typedef int mile;
```

```
typedef int kilometer;
```

```
void weak(mile lhs, kilometer rhs)
{
    lhs = rhs; ← ...
}
```



struct == definition

55

- a struct does introduce a new type name
 - ◆ use a wrapper type instead...

```
struct mile
{
    int value;
};
```



```
struct kilometer
{
    int value;
};
```



```
void strong(struct mile lhs, struct kilometer rhs)
{
    lhs = rhs; ←
    ...
}
```



struct == definition

- a struct wrapper does not introduces any extra runtime overhead

mile1.c

```
struct mile
{
    int value;
};

void f(int n)
{
    struct mile m = { n };
    if (m.value % 2)
        ...
}
```

mile2.c

```
typedef int mile;

void f(int n)
{
    mile m = n;
    if (m % 2)
        ...
}
```

```
>gcc -O2 -S mile1.c
>gcc -O2 -S mile2.c
>diff mile1.s mile2.s
    → no difference
```

struct layout

- **struct layout – the compiler...**
 - ◆ can insert padding between members and after the last member
 - ◆ cannot insert padding before the first element or re-order the members

```
#include <stddef.h> // offsetof

const size_t co = offsetof(struct wibble, c);
const size_t cs = offsetof(struct wibble, s);
const size_t ci = offsetof(struct wibble, i);
```



```
co == 0
cs >= co + sizeof(char)
ci >= cs + sizeof(short)
```

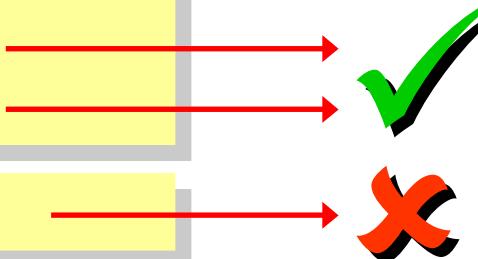
```
struct wibble
{
    char c;
    short s;
    int i;
};
```

- **structs support initialization and assignment**
 - ◆ not necessarily implemented as a `memcpy`
 - ◆ **some other implementation might be faster!**
e.g. member by member copying avoiding `memcpy` of many padding bytes
 - ◆ hence `==` and `!=` are not supported

```
struct wibble
{
    ...
};

struct wibble w = { ... };
struct wibble copy = w;
copy = w;

if (copy == w) ...
```



- a struct can contain an array
 - ◆ struct assignment copies the whole array!
 - ◆ no extra overhead compared to a memcpy

```
struct name
{
    char letters[64];
```



```
void strong(struct name * dst, const struct name * src)
{
    *dst = *src;
```



```
void strong(struct name * dst, const char * src)
{
    assert(strlen(src) < sizeof *dst);
    strcpy(dst->letters, src);
```



- **structs support designator identifiers**
 - ◆ allows for a small useful degree of ignorance

```
<stdlib.h>
7.22.6.2 The div ... Functions
div_t div(int numer, int denom);
The div...functions return a structure of
type div_t...The structures shall contain
→ (in either order)
the members quot (the quotient) and rem
(the remainder)...
```

```
struct div_t d = { 9, 6 };
```

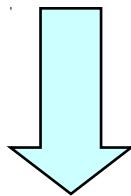


```
struct div_t d;
d.quot = 9;
d.rem = 6;
```



```
struct div_t d = { .quot = 9, .rem = 6 };
```

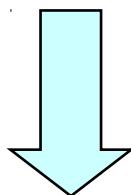




```
#define MAX_LEN (1024)  
char buffer[MAX_LEN];
```

Avoid the
preprocessor
when possible

worse

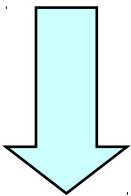


```
enum { MAX_LEN = 1024 };  
char buffer[MAX_LEN];
```



All uppercase is
reserved for the
preprocessor

better?



```
enum { max_len = 1024 };  
char buffer[max_len];
```



best?



```
struct x912_buffer  
{  
    char bytes[1024];  
};
```

anonymous enums

- useful for designators and switch labels

```
enum      { january, february, march,  
          ...  
          october, november, december  
};
```

```
const int days_in_month[] =  
{  
    [january] = 31,  
    [february] = 28,  
    ...  
    [november] = 30,  
    [december] = 31  
};
```

```
switch (...)  
{  
    case january: ...  
    case february: ...  
    ...  
    case november: ...  
    case december: ...  
}
```



- enums cannot be forward declared
 - ◆ or have cyclic dependencies
 - ◆ so never any need for a tag name

weak enum

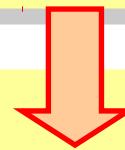
```
typedef enum suit
{
    clubs, diamonds, hearts, spades
} suit;
```

```
enum suit trumps;
suit lead;
```



```
typedef enum
{
    clubs, diamonds, hearts, spades
} suit;
```

```
enum suit trumps;
suit lead;
```



- **enums are very weakly typed**
 - ◆ an enum's enumerators are of type integer, not of the enum type itself!

weak enum

```
enum suit
{
    clubs, diamonds, hearts, spades
};
```



```
enum season
{
    spring, summer, autumn, winter
};
```



```
void weak(enum suit trumps, enum season now)
{
    trumps = now;
```



stronger enums

- an enum can also be wrapped in a struct

```
struct suit
{
    enum
    {
        clubs, diamonds, hearts, spades
    } value;
};
```



```
struct season
{
    enum
    {
        spring, summer, autumn, winter
    } value;
};
```



- **struct wrapper provides strong typing**
 - ◆ expressions that shouldn't compile don't
- **enum enumerators still available**
 - ◆ important for compile time constructs, eg switch
- **wrapper type is a struct**
 - ◆ forward declaration now possible

```
void strong(struct suit trumps, struct season now)
{
    trumps = now;           ← X

    switch (now.value)
    {
        case spring: ...
        case summer: ...
        case autumn: ...
        case winter: ...
    }
}
```



- a struct wrapper does not introduce any extra runtime overhead

suit1.c

```
struct suit
{
    enum { clubs, diamonds, hearts, spades } value;
};

void f(int n)
{
    struct suit trumps = { n % 2 ? clubs : diamonds };
    if (trumps.value == clubs)
        ...
}
```

stronger enums

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- a struct wrapper does not introduce any extra runtime overhead

suit2.c

```
enum suit
{
    clubs, diamonds, hearts, spades
};

void f(int n)
{
    enum suit trumps = n % 2 ? clubs : diamonds;
    if (trumps == clubs)
        ...
}
```

```
>gcc -O2 -S suit1.c
>gcc -O2 -S suit2.c
>diff suit1.s suit2.s
      → no difference
```

- what might this look like if refactored to a wrapped enum?

exercise

```
#define PKG_ID          0
#define PKG_VERSION      3
#define PKG_CKSUM         4
#define PKG_FILESIZE      8
#define PKG_FILE_CKSUM    12
...
...
```



an answer

```
enum
{
    package_offset_id = 0,
    package_offset_version = 3,
    package_offset_checksum = 4,
    package_offset_filesize = 8,
    package_offset_file_checksum = 12,
};
```

Objects

Users care about how easy objects are to use and how hard objects are to misuse. This is called Affordance.

Users don't want to know or care about how hard objects are to make*. This is called Ignorance/Apathy.

Users care about only what they care about! This is called Selfishness.

(in)consistency

```
<stdio.h>
```

```
int fsetpos(FILE *, ...);  
int fprintf(FILE *, ...);  
int fscanf (FILE *, ...);
```



```
int fputc (... , FILE *);  
int fputs (... , FILE *);  
size_t fwrite(... , FILE *);
```



```
int main(int argc, char * argv[])...
```

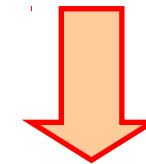
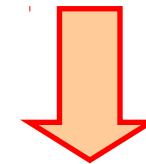
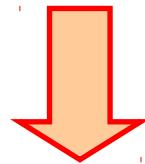
```
char * fgets(char * s, int n, FILE *);
```

• 7.14.1.1 The signal function

- ◆ if the request can be honoured, the signal function returns the value of func for the most recent successful call to signal for the specified signal sig.

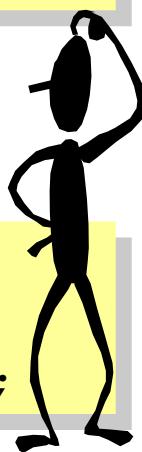
<signal.h>

```
void (* signal(int sig, void (*func)(int))) (int); ?
```



```
typedef void (*signal_handler) (int sig);
```

```
signal_handler signal(int sig, signal_handler func);
```



• 6.5.2.5 Compound literals

- ♦ para 5 – if the compound literal occurs outside the body of a function, the object has static storage duration; ...

```
int * p = (int[]) {1,2,3,4};
```

as-if

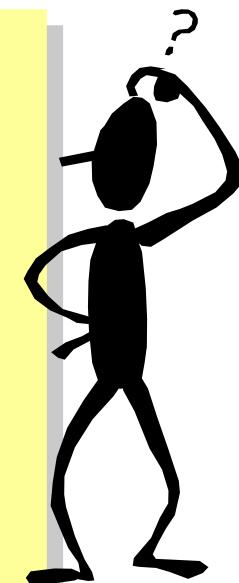
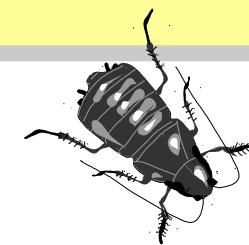
```
int $[] = { 1,2,3,4 };  
int * p = $;
```

• 6.5.2.5 Compound literals

- ◆ para 5 – if the compound literal occurs outside the body of a function, the object has static storage duration;

otherwise it has automatic storage duration associated with the enclosing *block*.

```
int eg(int i, int j)
{
    int * p;
    if (i == j)
        p = (int[]){ i, i };
    else
        p = (int[]){ j, j };
    return *p;
}
```



• 6.8.4 Selection statements

- ♦ para 3 – A selection statement is a block whose scope is a strict subset of the scope of its enclosing block. Each associated substatement is also a block whose scope is a strict subset of the scope of the selection statement.

block scope



```
void f(void)
{
    if (...)

    else ...
}
```

blocks

c89 blocks != c99/c11 blocks

```
void f(void)
```

```
{
```

```
if (...)
```

```
{ ... }
```

```
else
```

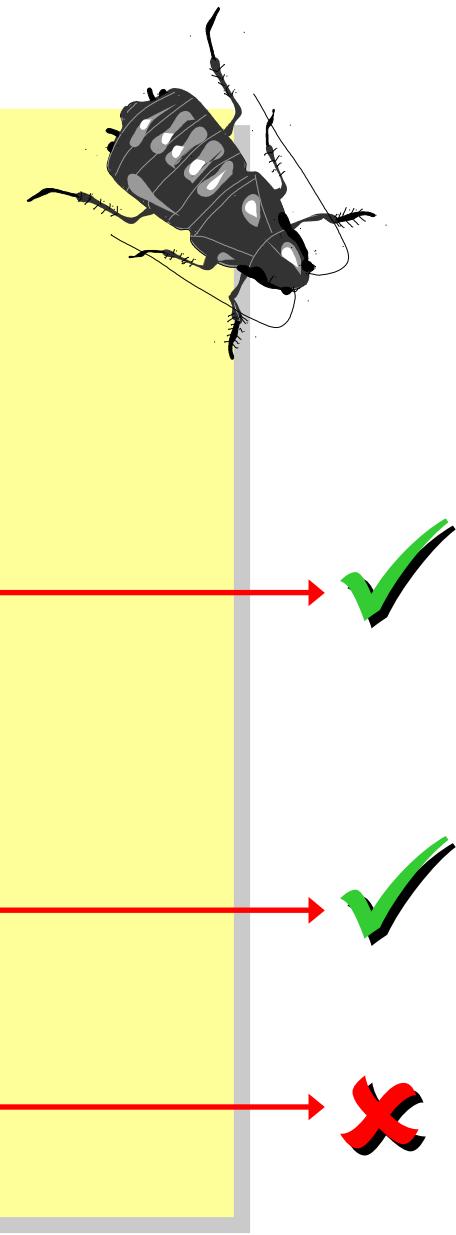
```
{ ... }
```

```
}
```

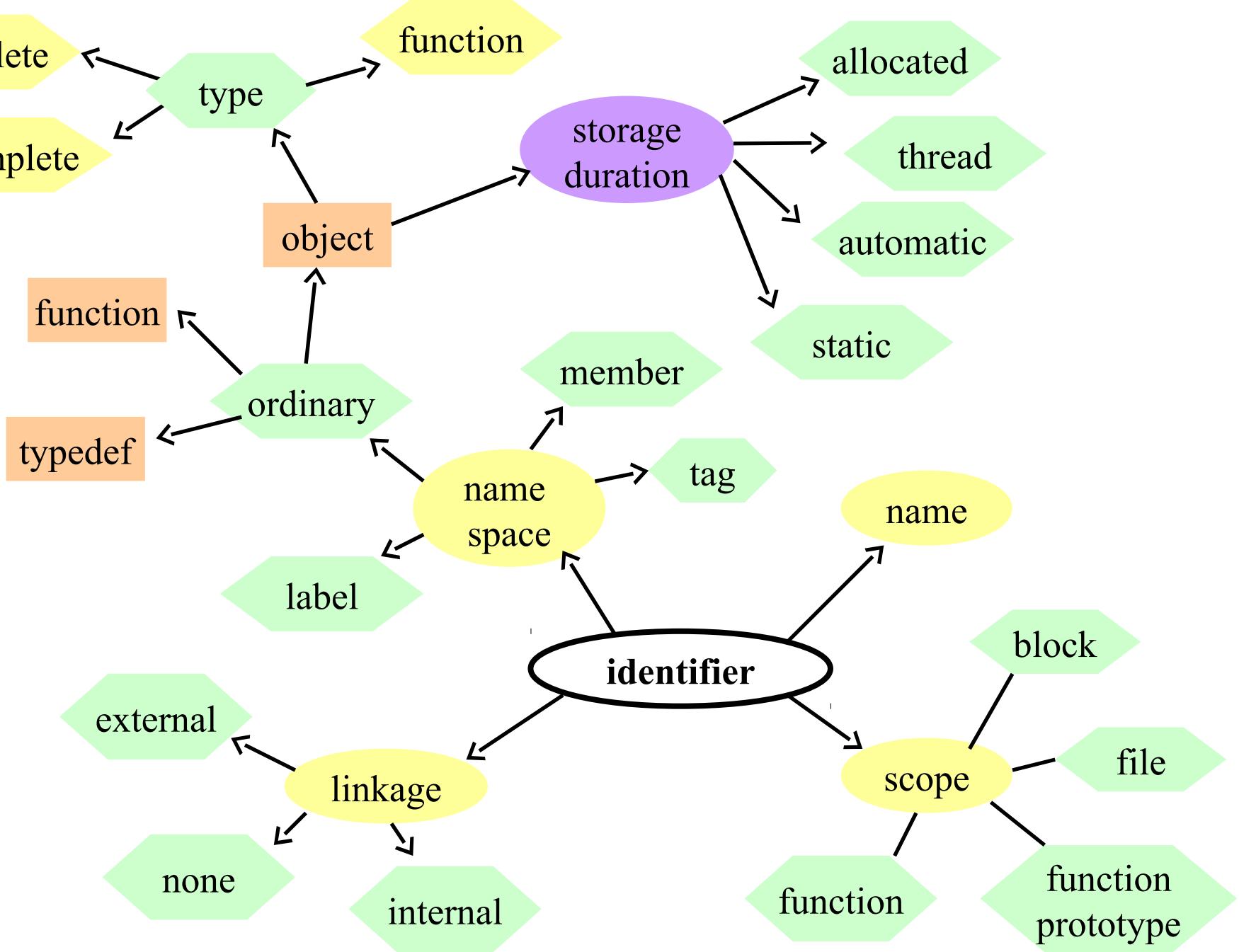
compound literals

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```
int eg(int i, int j)
{
    int * p;
    {
        if (i == j)
        {
            int $[] = { i, i };
            p = $;
        }
        else
        {
            int $[] = { j, j };
            p = $;
        }
    }
    return *p;
}
```



identifiers



scope-linkage

```
/* file scope */

typedef int typedef_no_linkage ;

struct stag_no_linkage { int member_no_linkage; };
union utag_no_linkage { int member_no_linkage; };
enum etag_no_linkage { member_no_linkage, };

static int object_internal_linkage;
extern int object_external_linkage;
    int object_external_linkage;

static void function_internal_linkage(void) {}
extern void function_external_linkage1(void) {}
    void function_external_linkage2(void) {}
```

scope-linkage

```
void function_prototype_scope(
    /* typedef illegal here */

    struct stag_no_linkage { int member_no_linkage; },
    union utag_no_linkage { int member_no_linkage; },
    enum etag_no_linkage {     member_no_linkage, },
    int object_no_linkage
);
```

```
void function_scope(void)
{
    label_no_linkage: ;
}
```

scope-linkage

```
void block_scope(void)
{
    typedef int __no_linkage;

    struct stag__no_linkage { int member__no_linkage; };
    union utag__no_linkage { int member__no_linkage; };
    enum etag__no_linkage {     member__no_linkage, };

        int object__no_linkage1;
    static int object__no_linkage2;
    extern int object__external_linkage;

    /* illegal - 6.7.1 paragraph 5 (pedantic) */
    static void function__internal_linkage(void);

    extern void function__external_linkage(void);
    void function__external_linkage(void);
}
```

Sequencing

- 5.1.2.3 Program execution. Paragraph 3
 - ◆ Sequenced before is a ... relation between evaluations executed by a single thread, which induces a partial order among those evaluations.
 - ◆ The presence of a sequence point between the evaluations of expressions A and B implies that every value computation and side effect associated with A is sequenced before every value computation and side effect associated with B.
 - ◆ If A is not sequenced before or after B, then A and B are unsequenced



A sequence point is a point of stability; a point in the program's execution sequence where all previous side-effects will have taken place and where all subsequent side-effects will not have taken place.

• 6.5 Expressions

- ♦ para 2 – If a side effect on a scalar object is unsequenced relative to either a different side effect on the same scalar object or a value computation using the value of the same scalar object, the behavior is undefined.

```
n = n++;
```

Undefined if n= (side effect on n) is unsequenced relative to n++ (different side effect on n)

```
n + n++;
```

Undefined if n (value computation of n) is unsequenced relative to n++ (side effect on n)

• 6.5 Expressions

- ♦ para 3 – Except as specified later, side effects and value computations of subexpressions are unsequenced.

```
n = n++;
```

Undefined behavior.

Assignment does not introduce a sequence point.



```
n + n++;
```

Undefined behavior.

Addition does not introduce a sequence point.



The default is that subexpressions are unsequenced.

- **sequence points occur...**
 - ◆ **at the end of a full expression**
 - **a full expression is an expression that is not a sub-expression of another expression or declarator (6.8 p4)**
 - ◆ **after the first operand of these operators**
 - **&& logical and (6.5.13 p4)**
 - **|| logical or (6.5.14 p4)**
 - **? : ternary (6.5.15 p4)**
 - **, comma (6.5.17 p2)**
 - ◆ **after evaluation of all arguments and function expression before a function call (6.5.2.2 p10)**
 - ◆ **at the end of a full declarator (6.7.6 p3)**

• 6.8 Statements and blocks

- ♦ para 4 – A full expression is an expression that is not part of another expression or declarator.

```
int function(int value)  
{
```

```
    int inside = [red box];
```

```
[red box];
```

```
if ([red box]) ...
```

```
switch ([red box]) ...
```

```
while ([red box]) ...
```

```
do ([red box]) ...
```

```
for ([red box]; [red box]; [red box]) ...
```

```
return [red box];
```

- an initializer;

- the expression in an expression statement;

- the controlling expression in a selection statement...;

- the controlling expression of a while or do statement;

- each of the (optional) expressions in a for statement;

- the (optional) expression in a return statement;

- when is a comma a sequence point?

exercise

```
int x    = f( ++o , ++o );
```

```
int x    =      ++o , ++o;
```

```
int x    =      (++o , ++o);
```



- when it's an operator but not when it's a punctuator

```
int x    = f( o++ , o++ );
```

punctuator

```
int x    =      o++ , o++;
```

X

```
int x    =      (o++ , o++);
```

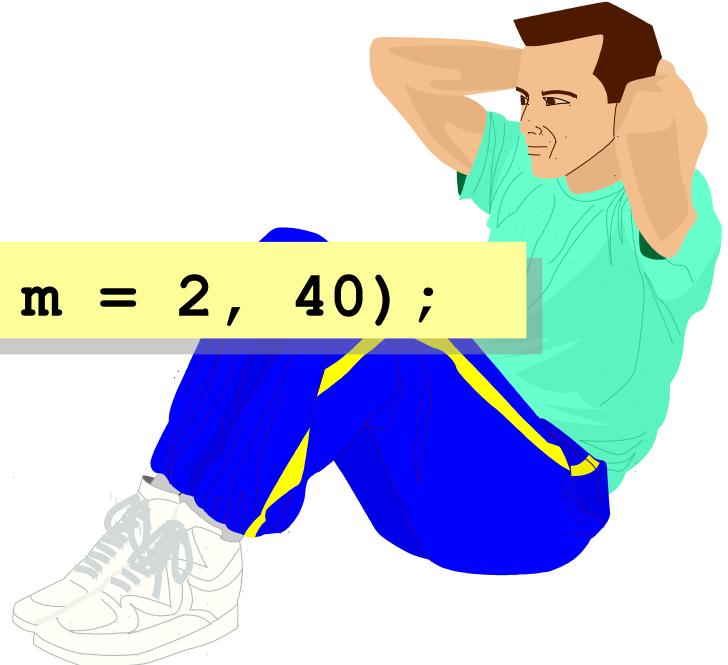
operator

another exercise

91

- in this very tricky statement...
 - ◆ where are the sequence points?
 - ◆ what are the operators?
 - ◆ what is their relative precedence?
 - ◆ what is affected by what?
 - ◆ how many times is m modified between sequence points?
 - ◆ is it undefined?

```
(10, m = 1, 20) + (30, m = 2, 40);
```



another exercise

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- what does this print?

```
#include <stdio.h>

int glob = 0;

int f(int value, int * ptr)
{
    if (value == *ptr)
    {
        printf("value == *ptr\n");
    }
    if (value != *ptr)
    {
        printf("value != *ptr\n");
    }
    return 1;
}

int main(void)
{
    return (glob = 1) + f(glob, &glob);
}
```



Representation

representation?

A general principle of coding

**Use as little representation
information as you can.**

**Use as little representation
information as you can.**



6.2.6 Representations of types

6.2.6.1 General

para 4 – Values stored in non-bit-field objects of any other object type consist of $n \times \text{CHAR_BIT}$ bits, where n is the size of that type, in bytes. The value may be copied into an object of type `unsigned char [n]` (e.g., by `memcpy`); the resulting set of bytes is called the object representation of the value.

To gain access to the bits comprising the representation of an object you must use the address of the object as a pointer to an `unsigned char`. This type alone guarantees access to all bits in all bytes.

6.2.6 Representations of types

6.2.6.2 Integer types

para 1 – For unsigned integer types other than unsigned char, the bits of the object representation shall be divided into two groups; value bits and padding bits...If there are N value bits, each bit shall represent a different power of 2 ... using a pure binary representation; this shall be known as the value representation. The value of any padding bits are unspecified.



Suppose CHAR_BIT == 8 and sizeof(int) == 4

This does not guarantee that int is a 32 bit integer type! Use INT_MAX to determine if int is a 32 bit integer.



x === y; implies memcmp(&x, &y, sizeof(x)) == 0
true or false? ←

?

LValues



The name lvalue comes originally from the assignment expression $E1 = E2$, in which the left operand $E1$ is required to be a (modifiable) lvalue. It is perhaps better considered as representing an object "locator value". What is sometimes called an "rvalue" is, in the Standard, described as the "value of the expression"

6.3.2.1 Lvalues, arrays, and function designators **para 1 – sentence 1**

An lvalue is an expression (with an object type other than void) that potentially designates an object; if an lvalue does not designate an object when it is evaluated, the behavior is undefined.

6.3.2.1 Lvalues, arrays, and function designators para 1 – sentence 3

A modifiable-lvalue is an lvalue that

- does not have array type
- does not have an incomplete type
- does not have a const-qualified type
- if it is a struct or union does not have any member...with a const-qualified type



An lvalue might be unmodifiable because...

- it is an array that's decayed into a pointer
- it has unknown size
- it is const qualified

6.3.2.1 Lvalues, arrays, and function designators

para 2 - Except when it is the operand of

- the `sizeof` operator
- the unary `&` operator
- the `++` operator
- the `--` operator
- the left operand of the `.` operator
- the left operand of an assignment operator

an lvalue that does not have an array type is converted to the value stored in the designated object (and is no longer an lvalue).



Lots of expressions start out as an lvalue and are implicitly converted into a value.

- these operators never yield lvalues

values

unary	! ~ + - ++ -- (T) &
arithmetic	* / % + -
shift	<< >>
relational	< > <= >= == !=
bitwise/boolean	& ^
boolean	&& ?:
assignment	= *= /= %= += -= ...
comma	,

- these expressions sometimes yield lvalues

primary	identifier
parentheses	()

- these operators sometimes yield lvalues

subscript	[]
arrow	->
dot	.
dereference	*

6.5.1 Primary Expressions

para 2 - An identifier is a primary expression, provided it has been declared as designating an object (in which case it is an Ivalue)...

```
int function(int m)
{
    m = 42; ←
```



- ◆ m designates an object and is an Ivalue
- ◆ m is a modifiable Ivalue
 - (not array, incomplete, const)
- ◆ m is not converted to a value
 - (left hand side of assignment)

6.5.1 Primary Expressions

para 5 - A parenthesized expression is a primary expression. Its type and value are identical to those of the unparenthesized expression.

```
int function(int m)
{
    (m) ++;
}
```



- ◆ m is an lvalue (previous slide)
- ◆ so (m) is an lvalue
- ◆ (m) is a modifiable lvalue
 - (not array, incomplete, const)
- ◆ (m) is not converted to a value
 - (operand of ++)

6.5.2.3 Structure and union members

para 3 - A postfix expression followed by the . operator and an identifier designates a member of a structure or union. The value is that of the named member, and is an Ivalue if the first expression is an Ivalue

```
void f(struct wibble w)
{
    w.member = 42;
}
```



- ◊ w designates an object and is an Ivalue
- ◊ w is a modifiable Ivalue
 - (not array, incomplete, const)
- ◊ w is not converted to a value
 - (left operand of . operator)
- ◊ so w.member is also an Ivalue
- ◊ w.member is not converted to a value
 - (left hand side of assignment)

- is this a conforming program?
- if not why not?
 - ◆ what clause? what paragraph?

```
struct wibble
{
    int member;
};

struct wibble f(void)
{
    struct wibble w;
    ...
    return w;
}

void use(void)
{
    f().member--;
}
```



- no, it's not a conforming program
 - ◆ 6.3.2.1 paragraph 2 (see slide 93)

```

struct wibble
{
    int member;
};

struct wibble f(void)
{
    struct wibble w;
    ...
    return w;
}

void use(void)
{
    f().member--;
}

```

- w designates an object and is an lvalue
- w is converted to a value
- f() is a value so f().member is also a value
- you can't do -- on a value

6.5.2.3 Structure and union members

para 4 - A postfix expression followed by the → operator and an identifier designates a member of a structure or union. The value is that of the named member of the object to which the first expression points to, and is an Ivalue.

```
void f(struct wibble w)
{
    wibble * ptr = &w;
    ptr->member = 42;
}
```



- ◆ **ptr→member is an Ivalue**
- ◆ **ptr→member is a modifiable Ivalue**
 - (not array, incomplete, const)
- ◆ **ptr→member is not converted to a value**
 - (left hand side of assignment)

- is this a conforming program?
- if not why not?
 - ◆ what clause? what paragraph?

```
struct wibble
{
    int member;
};

struct wibble * f(void)
{
    struct wibble w;
    ...
    return &w;
}

void use(void)
{
    f () ->member = 42;
}
```



- no, it's not a conforming program
 - ◆ 6.3.2.1 paragraph 1 (see slide 91)

answer

```
struct wibble
{
    int member;
};

struct wibble * f(void)
{
    struct wibble w;
    ...
    return &w;
}

void use(void)
{
    f() ->member = 42;
}
```

- w has auto storage class
- f() points to an object whose lifetime has ended
- f() → member is an object whose lifetime has ended

6.5.3.2 Address and indirection operators

para 4 - The unary `*` operator denotes indirection. If the operand ... points to an object, the result is an Ivalue designating the object.

```
void star(struct wibble w)
{
    struct wibble * ptr = &w;
    *ptr = w;
}
```



- ◆ **ptr points to an object**
- ◆ ***ptr is an Ivalue**
- ◆ ***ptr is a modifiable Ivalue**
 - (not array, incomplete, const)
- ◆ ***ptr is not converted to a value**
 - (left hand side of assignment)

6.5.3.2 Address and indirection operators

para 3 - The unary & operator yields the address of its operand. ... If the operand is the result of a unary * operator, neither that operator, nor the & operator is evaluated and the result is as if both were omitted, ... and the result is not an lvalue.

```
void cancel_one_way(struct wibble w)
{
    *&w = w; ← ✓
}
```

```
void cancel_other_way(struct wibble w)
{
    wibble * ptr;

    ptr = &w; ← ✓
    &*ptr = &w; ← ✗
}
```



6.5.4 Cast operators

para 2 - Unless the type name specifies a void type, the type name shall specify atomic, qualified, or unqualified scalar type and the operand shall have scalar type.

Footnote: A cast does not yield an Ivalue.

```
void casting(void)
{
    int x;

    x = 42;
}
```

x = 42;



(int)x = 42;



cast is not lvalue

(int[]) 42;



int[] is not scalar type

(cast) operator



In C++ sometimes the result of a cast is an lvalue

6.5.2.5 Compound literals

para 4 - A postfix expression that consists of a parenthesized type, followed by a brace enclosed list of initializers is a compound literal. It provides an unnamed object whose value is given by the initializer list. ...
para 5 - The result is an Ivalue.

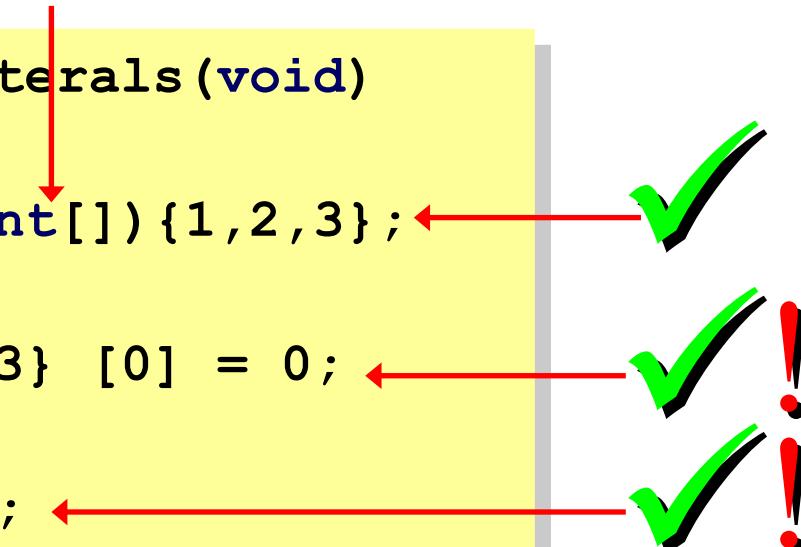
compound literals

this is not a cast

```
void compound_literals(void)
{
    int x[] = (int[]) {1,2,3};
```

```
(int[]) {1,2,3} [0] = 0;
```

```
(int) {1} = 2;
```



6.5.16 Assignment operators

para 3 - An assignment stores a value in the object designated by the left operand. An assignment expression has the value of the left operand after the assignment, but is not an Ivalue.

```
void assignment(void)
{
    int x;

    x = 42;           ←
    (x = 42) = 0;   ←
}
```



6.5.3.1 Prefix increment and decrement operators

para 1 - The operand of the prefix increment or decrement operator shall have atomic, qualified, or unqualified real or pointer type, and shall be a modifiable lvalue.

para 2 - ... The result is the new value of the operand after incrementation. The expression ++E is equivalent to $(\text{E}+=1)$

```
void increment(void)
{
    int x = 0;
    x++ = 42;           ← X
    ++x = 42;           ← X
}
```



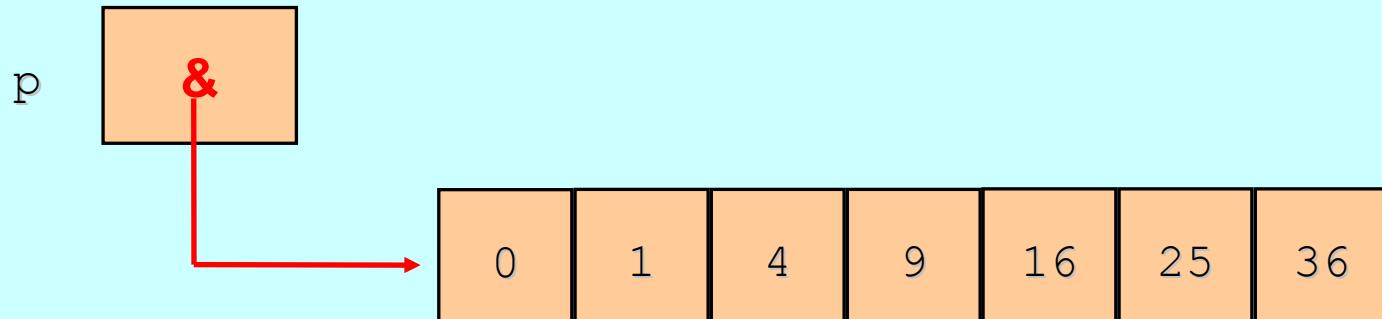
++x is accidentally an lvalue in C++

Arrays

- an aggregate initializer list can apparently be cast to an array type
 - ◆ known as a compound literal

```
int * p =  
    (int []){ 0,1,4,9,16,25,36 };
```

array literal

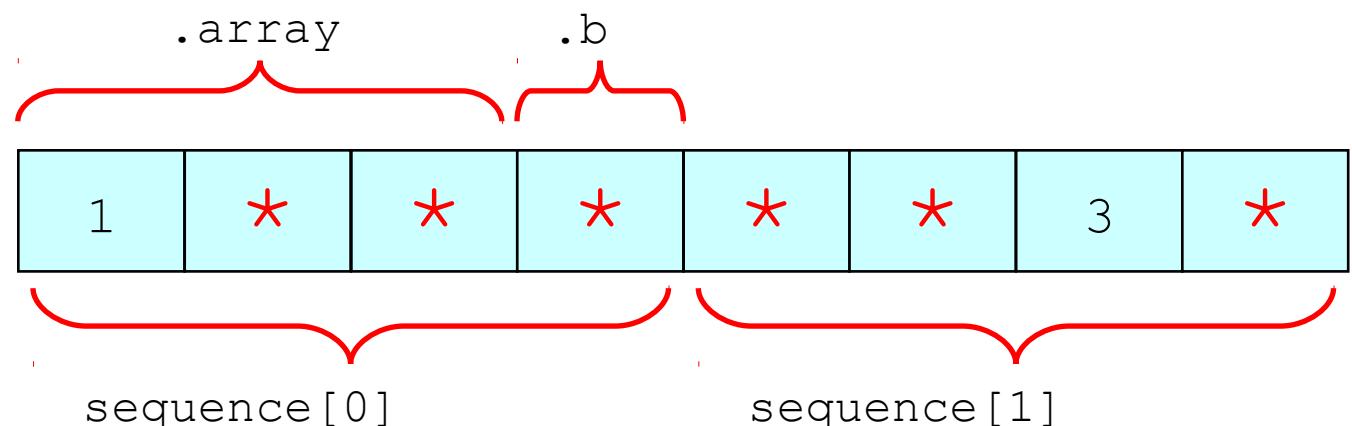


- arrays and struct may contain each other
 - ◆ [int] and .identifier designators can be combined

struct containing array

```
struct s
{
    int array[3];
    int b;
};
```

```
struct s sequence[] =
{
    [0].array = { 1 },
    [1].array[2] = 3
};
```



*default value

- only the top-level array decays into a pointer
 - ◆ the size of sub arrays remains part of the type

```
void print(int nrows, int matrix[2][3]);  
void print(int nrows, int matrix[ ][3]);  
void print(int nrows, int (*matrix)[3]);
```

equivalent

```
int main(void)  
{  
    int grid[2][3] = {{0,1,2},{3,4,5}};  
    ...  
    print(2, grid);  
}
```

```
void illegal(int matrix[ ][ ]) ...
```



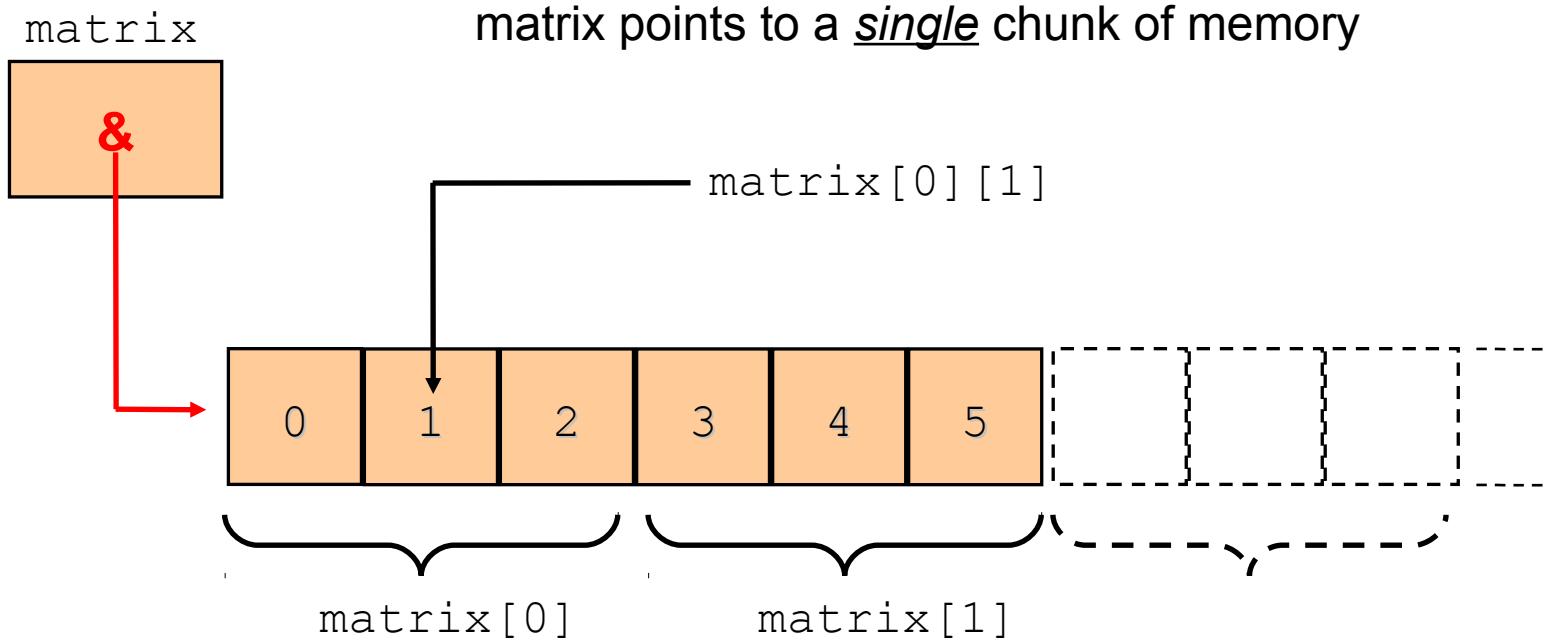
pointer to array

```
int (*matrix) [3]
```

```
int (*matrix) [3]
```

```
int (*matrix) [3]
```

matrix is a pointer
to zero, one, or more
array(s) of three ints



- an array of pointers can mimic a 2d array
 - ◆ each pointer points to an array
 - ◆ aka Illiffe vector aka dope vector

note this is `int *ragged[2]` and not `int (*ragged)[2]`

```
void print(int nrows, int ncols, int * ragged[2]);  
void print(int nrows, int ncols, int * ragged[ ]);  
void print(int nrows, int ncols, int ** ragged);
```

equivalent

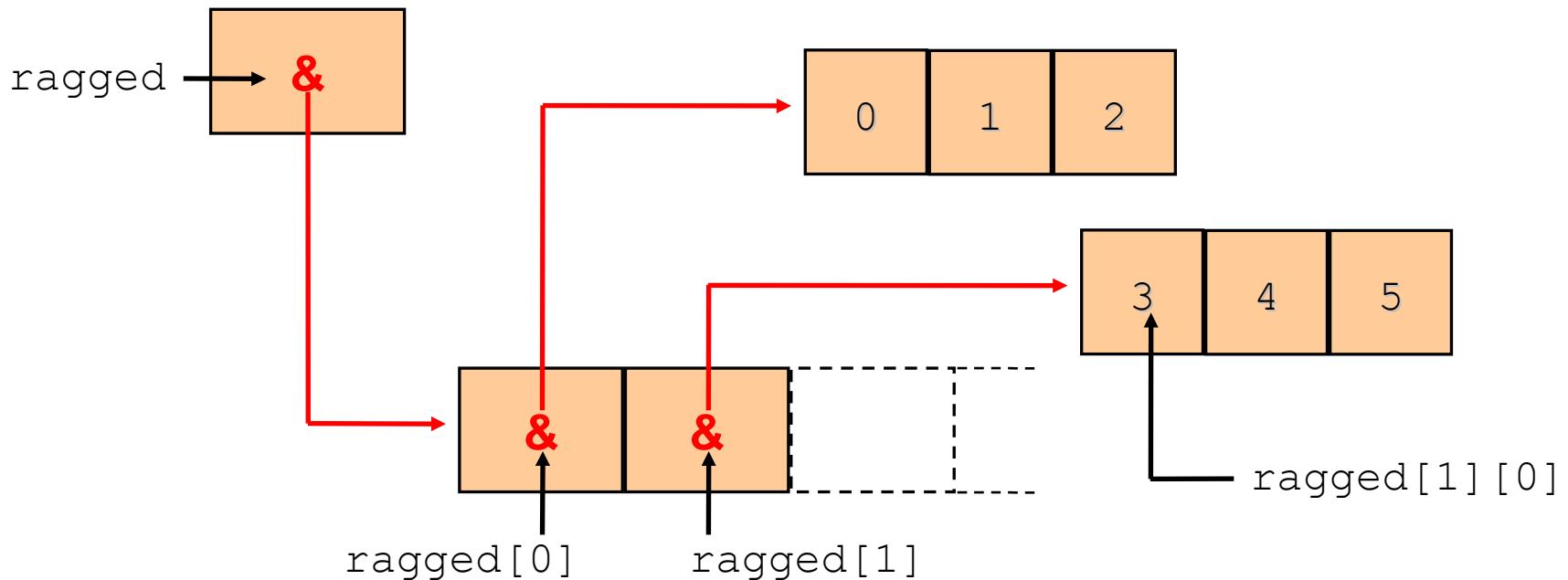
```
int main(void)  
{  
    int vec1[] = { 0, 1, 2 };  
    int vec2[] = { 3, 4, 5 };  
    int * grid[2] = { vec1, vec2 };  
  
    print(2, 3, grid);  
}
```

123

```
int * ragged[]
```

ragged is an array
of
pointers
to zero, one, or more
int(s)

array of pointers



ragged array example

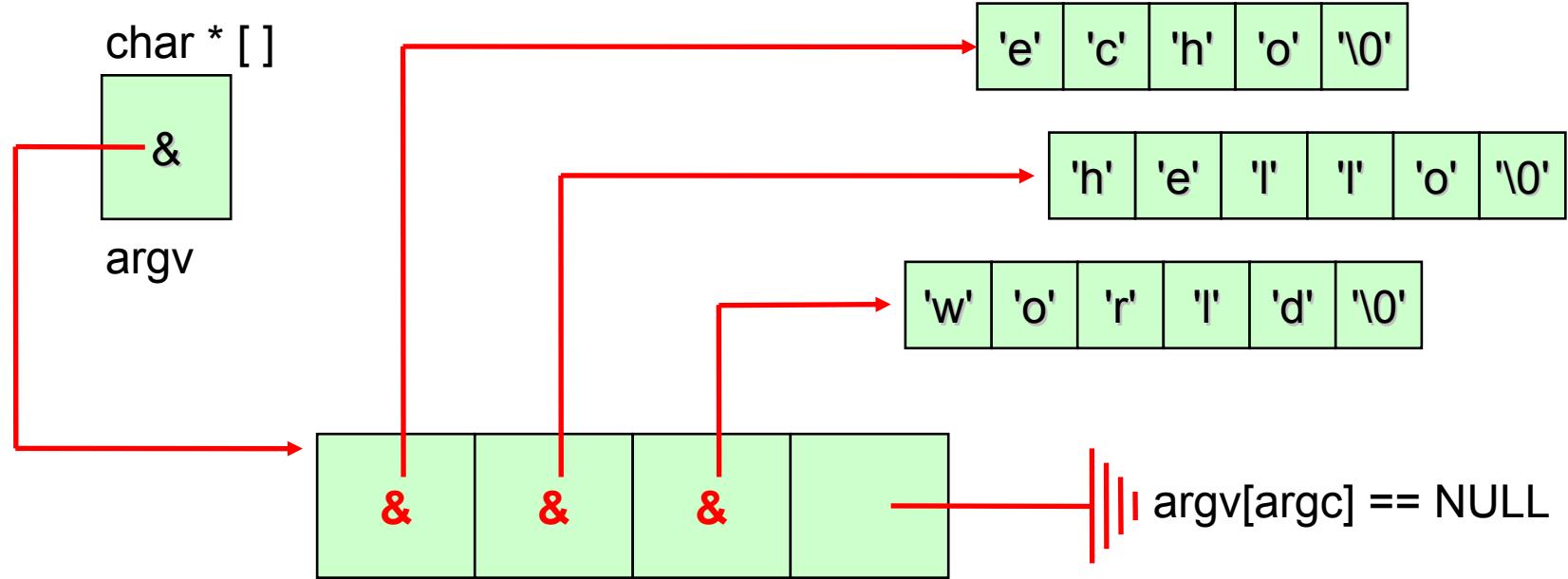
124

echo.c

```
#include <stdio.h>

int main(int argc, char * argv[])
{
    for (int at = 0; at != argc; at++)
        printf("%s ", argv[at]);
    putchar('\n');
}
```

```
>echo hello world
```



variable length arrays

125

- VLA's - four restrictions



```
void vla(int n)
{
    int ok[n];
    static int g[n];
    extern int f[n];
    struct tag
    {
        int x[n];
    };
    extern int size;
    int array[size];
}
```

An object with static storage duration cannot have a variable length array type

An object with linkage cannot have a variable length array type

An identifier other than a simple identifier cannot have a variable length array type

A file scope identifier cannot have a variable length array type

variable length arrays

- VLA's make multi-dimensional array parameters much more useful and reusable

```
void print(int n, int m, int matrix[ n ] [ m ] );
```

```
void print(int n, int m, int matrix[ n ] [ m ] )  
{  
    ...  
}
```

n and m must be declared before matrix

```
int main(void)  
{  
    int matrix[][][3] = {{ 0, 1, 2 }, { 3, 4, 5 }};  
    print(2, 3, matrix);  
}
```

• 6.7.6.2 Array declarators

- ♦ para 4 – If the size is * instead of being an expression, the array type is a variable length array type of unspecified size, which can only be used in declarations with function prototype scope

```
void print(int n, int m, int matrix[ * ] [ * ] );
```

```
void print(int n, int m, int matrix[ n ] [ m ] )  
{  
    ...  
}
```

- 6.7.6.2 Array declarators

- ♦ para 5 – if the size is an expression that is not an integer constant expression ... each time it is evaluated it shall have a value greater than zero.

```
int f(int m);  
  
void print(int n, int vla[ f(n) + 4 ])  
{  
    int another_vla[ f(f(n) + f(3)) ];  
    ...  
}
```

• 6.5.3.4 The `sizeof` operator

- ◆ para 2 – If the type of the operand is a variable length array type, the operand is evaluated; otherwise, the operand is not evaluated and the result is an integer constant

```
void examples(int n, int vla[ f(n) ])
{
    ...sizeof vla
    int fla[42];
    ...sizeof fla
}
```

compile-time evaluation

run-time evaluation

• 6.7.6.3 Function declarators

- ◆ para 7 - If the keyword static also appears within the [and] of the array type derivation, then for each call to the function, the value of the corresponding argument shall provide access to the first element of an array with at least as many elements as specified by the size expression

```
void function(double f[static 16])  
{  
    ...  
}
```



f is non-null and points to at least 16 doubles

- 6.7.6.3 Function declarators
 - ◊ para 7 – A declaration of a parameter as "array of type" shall be adjusted to "qualified pointer to type", where the type qualifiers (if any) are those specified within the [and] of the array type derivation



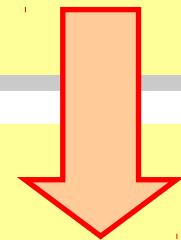
```
void function(double f[])
{
    f = 0;
}
```



'also restrict'



```
void function(double f[const])
{
    f = 0;
}
```



'adjustment'



```
void function(double * const f)
{
    f = 0;
}
```

- complete arrays can be `typedef'd`

```
void example(int m)
{
    typedef int fixed[42];

    typedef int variable[m] ;

    fixed f;
    variable v;
    ...
}
```

typedef

```
typedef int table[];  
  
void example(void)  
{  
    table t1 = { 1,2 };  
  
    printf("%zd\n", sizeof(t1));  
  
    table t2 = { 1,2,3,4 };  
  
    printf("%zd\n", sizeof(t2));  
}
```

2 * sizeof(int)

4 * sizeof(int)

Pointers

- an array expression usually "decays" into a pointer to element zero

```
void display(size_t size, wibble * first);  
void display(size_t size, wibble first[]);
```

these two declarations are equivalent*

```
wibble table[42] = { ... };
```

```
display(42, table);  
display(42, &table[0]);
```

these two statements are equivalent

- 6.3.2.1 Lvalues, arrays, and function designators
 - ◊ para 3 - Except when it is the operand of
 - the sizeof operator
 - or the unary & operator,
 - or is a string literal used to initialize an array,
 - ◊ an expression that has type "array of type" is converted to an expression with type "pointer to type" and points to the initial element of the array object and is not an lvalue

There are three exceptions



- what does this program print?
 - ◆ assume `sizeof(char*) == 8`

exercise

```
struct wibble
{
    char x[42];
};

struct wibble f(void);

void array_decay(void)
{
    char x[42];

    printf("%zd\n", sizeof(f().x));

    printf("%zd\n", sizeof(x));

    printf("%zd\n", sizeof(0, x));
}
```



```
struct wibble
{
    char x[42];
};

struct wibble f(void);

void array_decay(void)
{
    char x[42];

    printf("%zd\n", sizeof(f().x));           → 42
    printf("%zd\n", sizeof(x));                → 42
    printf("%zd\n", sizeof(0, x));             → 8
}
```

- strings are arrays of char
 - ◆ automatically terminated with a null character, '\0'
 - ◆ a convenient string literal syntax

```
char greeting[] = "Bonjour";
```

equivalent to

```
char greeting[] =  
{ 'B', 'o', 'n', 'j', 'o', 'u', 'r', '\0' };
```



There is no decay in this case

- what does this program print?

```
void array_decay_or_not(void)
{
    char x[42];

    printf("%zd\n",
           (char*)(x+1) - (char*) x);

    printf("%zd\n",
           (char*)(&x+1) - (char*)&x);

    printf("%zd\n",
           (&x+1) - &x);
}
```



```
void array_decay_or_not(void)
{
    char x[42];

    printf("%zd\n",
           (char*)(x+1) - (char*) x);

    printf("%zd\n",
           (char*)(&x+1) - (char*)&x);

    printf("%zd\n",
           (&x+1) - &x);
}
```

1

42

1

- C99/C11 library now uses **restrict** in its declarators where appropriate
 - ◆ says in code what would otherwise be said only in comments

```
void * memcpy(void * s1,  
             const void * s2,  
             size_t n);  
  
char * strcpy(char * s1,  
             const char * s2);
```

7.24 <string.h>

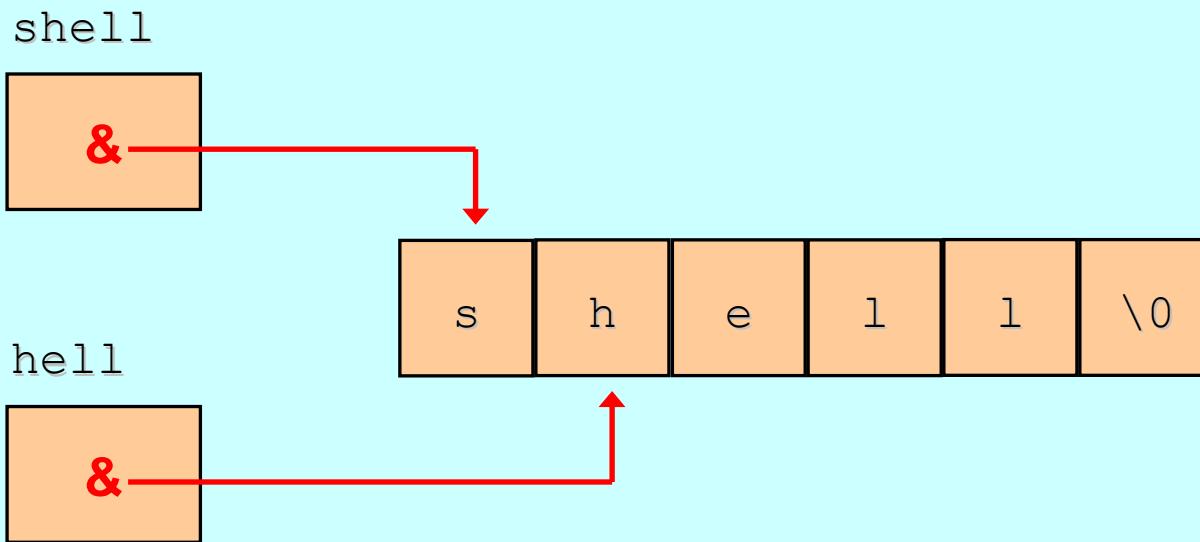
```
void * memcpy(void * restrict s1,  
             const void * restrict s2,  
             size_t n);  
  
char * strcpy(char * restrict s1,  
             const char * restrict s2);
```

If copying takes place between objects that overlap the behavior is undefined.

- duplicate string literals can be assigned to the same (static) storage location
 - ◆ be careful with **restrict**

```
const char * shell = "shell";
const char * hell = "hell";
```

S-hell



- **6.5.2.1 Array subscripting**
 - ◆ para 2 – The definition of the subscript operator [] is that $E1[E2]$ is identical to $(*(E1)+(E2))$
- **6.5.6 Additive operators**
 - ◆ para 8 – If both the pointer operand and the result point to elements of the same array object, or one past the last element of the array object, the evaluation shall not produce an overflow; otherwise, the behavior is undefined.



Any pointer arithmetic that takes a pointer outside of the pointed to object...is undefined behavior. There is no requirement that the pointer be dereferenced.

- which of these are conforming?

exercise

```
int array[10];  
  
int * p1 = (array + 20) - 19;  
  
int * p2 = array + 20 - 19;  
  
int * p3 = array + (20 - 19);  
  
int * p4 = array + 1;
```



```
int array[10];
```

```
int * p1 = (array + 20) - 19; 
```

```
int * p2 = array + 20 - 19; 
```

```
int * p3 = array + (20 - 19); 
```

```
int * p4 = array + 1; 
```

- **typedef'ing a pointer...**

```
typedef struct date * date;
```

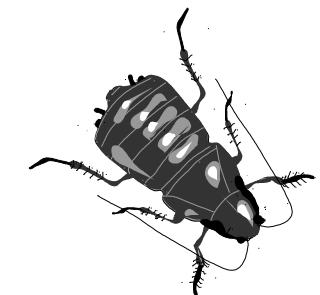
```
bool question(const date d);
```

...what is const?

is it the date pointer?

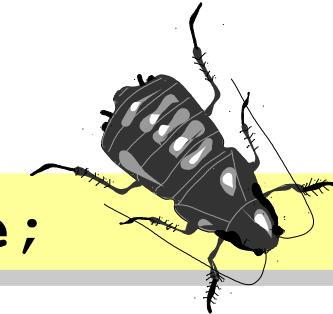
or

is it the date pointed to?



- the pointer is **const**!
- not the date pointed to!

```
typedef struct date * date;
```



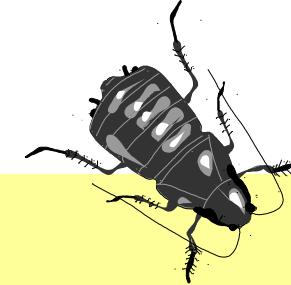
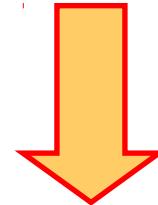
```
bool question(const date d);
```

equivalent

```
bool question(struct date * const d);
```

- so how about this...?
 - ◆ one typedef for plain ptr
 - ◆ another typedef for ptr to const

```
typedef struct date * date;
typedef const struct date * cdate;
```



```
void hide_ptr(date delay);
```

```
void hide_const_too(cdate delay);
```

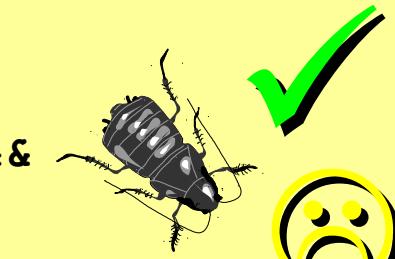
- NO! it's a bad bad idea
 - ◊ hiding the pointer inside a **typedef** is not a good idea

```
struct date
{
    int day;
    int month;
    int year;
};
```

→ **typedef struct date * date;**

```
bool date_equal(const date lhs, const date rhs)
{
    return lhs->day == rhs->day &&
           lhs->month == rhs->month &&
           lhs->year = rhs->year;
}
```

answer



Conversions

- 6.5.16 Assignment operators
 - ◆ para 3 – The type of an assignment expression is the type the left operand would have after lvalue conversion
- 6.5.16.1 Simple assignment
 - ◆ para 2 – The value of the right operand is converted to the type of the assignment expression

```
unsigned short x = 0;  
x = UINT_MAX;
```



Assignment is the only binary operator that can cause the type of one of its operands to be implicitly converted to a "narrower" type.

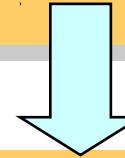
So `x = y;` ~~W~~ `x == y;` is not true

- 6.3.1.1 Booleans, characters, and integers
 - ◆ para 2 – If an int can represent all the values of the original type, the value is converted to an int; otherwise, it is converted to an unsigned int.
These are called the *integer promotions*.

```
char c1, c2;
```

```
c1 + c2
```

```
(int)c1 + (int)c2
```



Why does the compiler prefer ints?



• 6.5.2.2 Function calls

- ◊ para 6 – if the expression that denotes the called function does not include a prototype, the integer promotions are performed on each argument, and arguments that have type float are promoted to double. These are called the default argument promotions.

```
#include <stdio.h>

int main(void)
{
    return call(4, 2);
}

int call(double a, double b)
{
    return printf("%f, %f\n", a, b);
}
```



• 6.5.2.2 Function calls

- ♦ para 7 – if the expression that denotes the called function has a type that does include a prototype, the arguments are implicitly converted, as if by assignment, to the types of the corresponding parameters...

```
#include <stdio.h>

int call(double, double);

int main(void)
{
    return call(4, 2);
}

int call(double a, double b)
{
    return printf("%f, %f\n", a, b);
}
```



- 6.5.2.2 Function calls

- ♦ para 7 – The ellipsis notation in a function prototype declarator causes argument type conversions to stop after the last declared parameter. The default argument promotions are performed on the trailing arguments.

```
void variadic(char c, ...);
```

as if by assignment

default argument promotion

```
variadic('X', 'X');
```

- spot the bugs

exercise

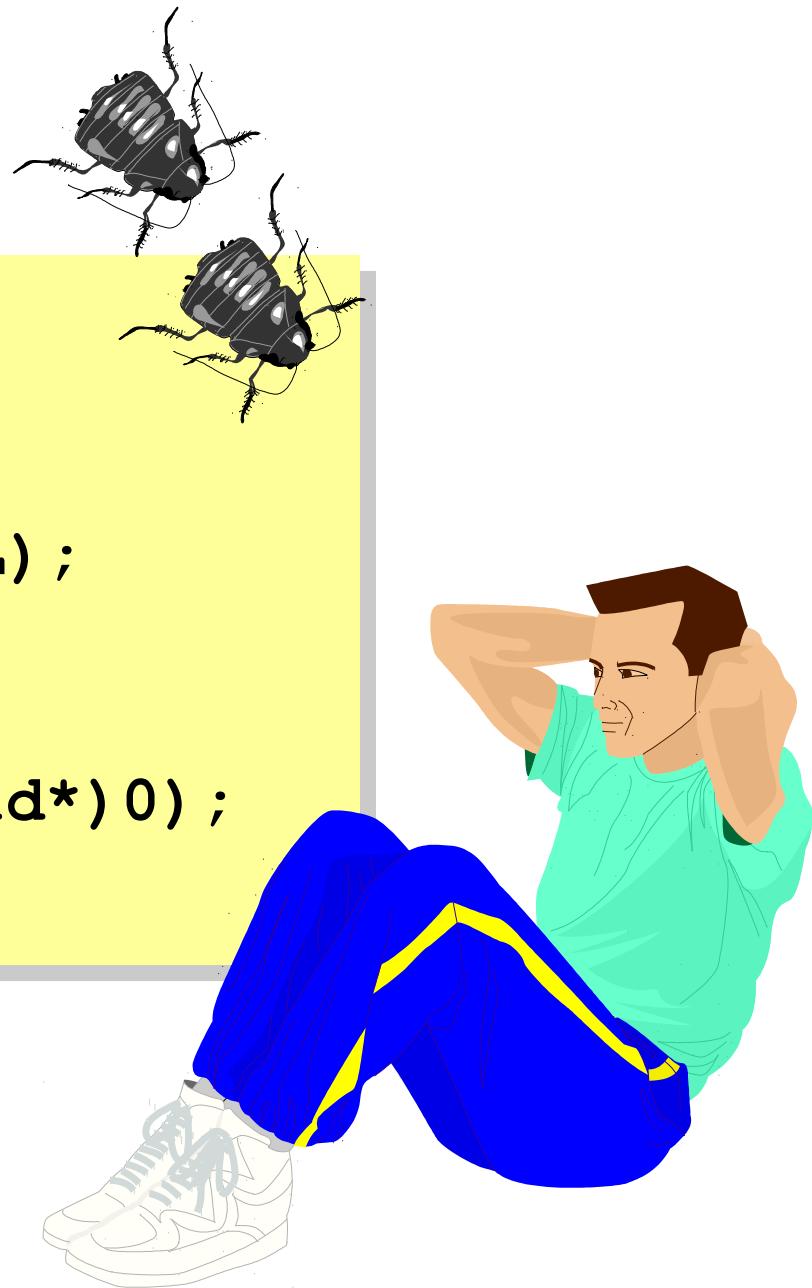
```
#include <stdio.h>

int main(void)
{
    printf("%p", NULL) ;

    printf("%p", 0) ;

    printf("%p", (void*) 0) ;

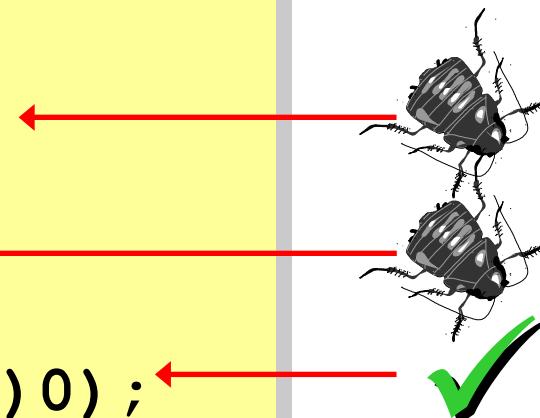
}
```



- only `(void*)0` is guaranteed to be a pointer
 - ◆ 0 is an int
 - ◆ NULL could be 0 too

```
#include <stdio.h>

int main(void)
{
    printf("%p", NULL) ;
    printf("%p", 0) ;
    printf("%p", (void*) 0) ;
}
```



- **<stdarg.h> provide type-unsafe access**
 - ◆ restrictions on all the **va_** macros (7.16.1.1)

<stdarg.h>

```
#include <stdarg.h>

int printf(const char * format, ...)
{
    va_list args;
    va_start(args, format);
    for (size_t at = 0; format[at]; at++)
    {
        switch (format[at])
        {
            case 'c':
                {
                    int param = va_arg(format, int);
                    char passed = (char)param;
                    ...
                }
            ...
        }
    }
    va_end(args);
}
```

char

int

char

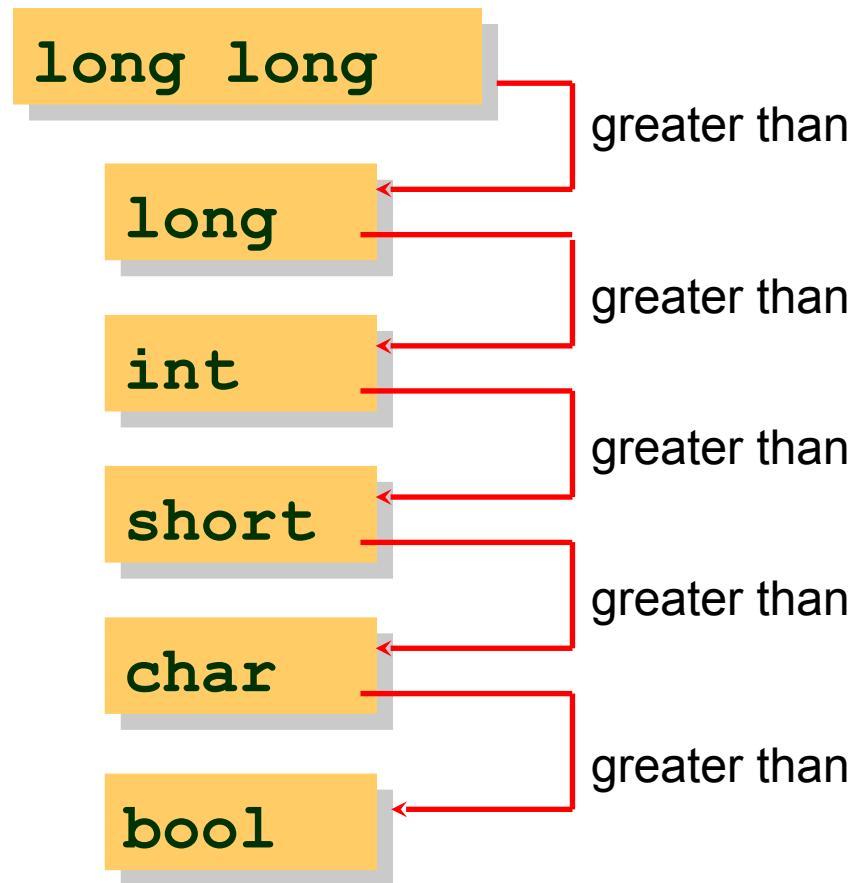
• 6.3.1.1 Booleans, characters, and integers

...

Every integer type has an *integer conversion rank*...

...

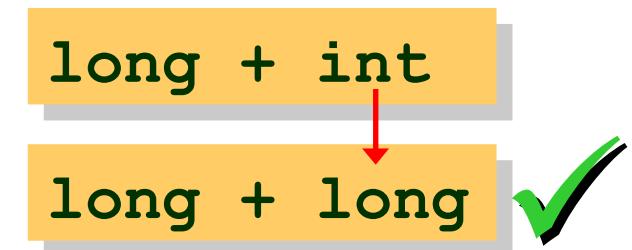
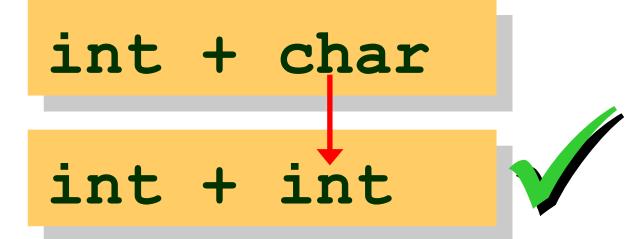
rank



- **6.3.1.8 Usual arithmetic conversions**
 - ◆ **part 1: the obvious conversion rule (safe)**

- ...
- ... [both operands have integer type]
- ...
- the *integer promotions* are performed on both operands

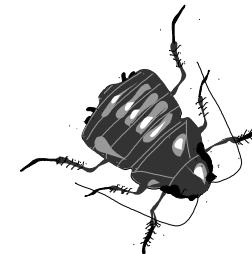
- If both operands have the same type, then no further conversion is needed.
- Otherwise, if both operands have signed integer types or both have unsigned integer types, the operand with the type of lesser integer conversion rank is converted to the type of the operand with greater rank.
- ...



- 6.3.1.8 Usual arithmetic conversions
 - part 2: the signed → unsigned rule (lossy)

- ...
- [one signed and one unsigned operand]
- ...
- Otherwise, if the operand that has unsigned integer type has rank greater or equal to the rank of the type of the other [signed] operand, then the operand with the signed integer type is converted to the type of the operand with the unsigned integer type.
-

unsigned long + int



unsigned long + unsigned long

a negative signed integer value can be converted into a large positive unsigned integer value!!

- 6.3.1.8 Usual arithmetic conversions

- ◆ part 3: the unsigned → signed rule (safe)

...

[one signed and one unsigned operand]

[rank(signed operand) > rank(unsigned operand)]

...

- Otherwise, if the type of the operand with signed integer type can represent all of the values of the type of the operand with unsigned integer type, then the operand with unsigned integer type is converted to the type of the operand with signed integer type.

long + unsigned int

?



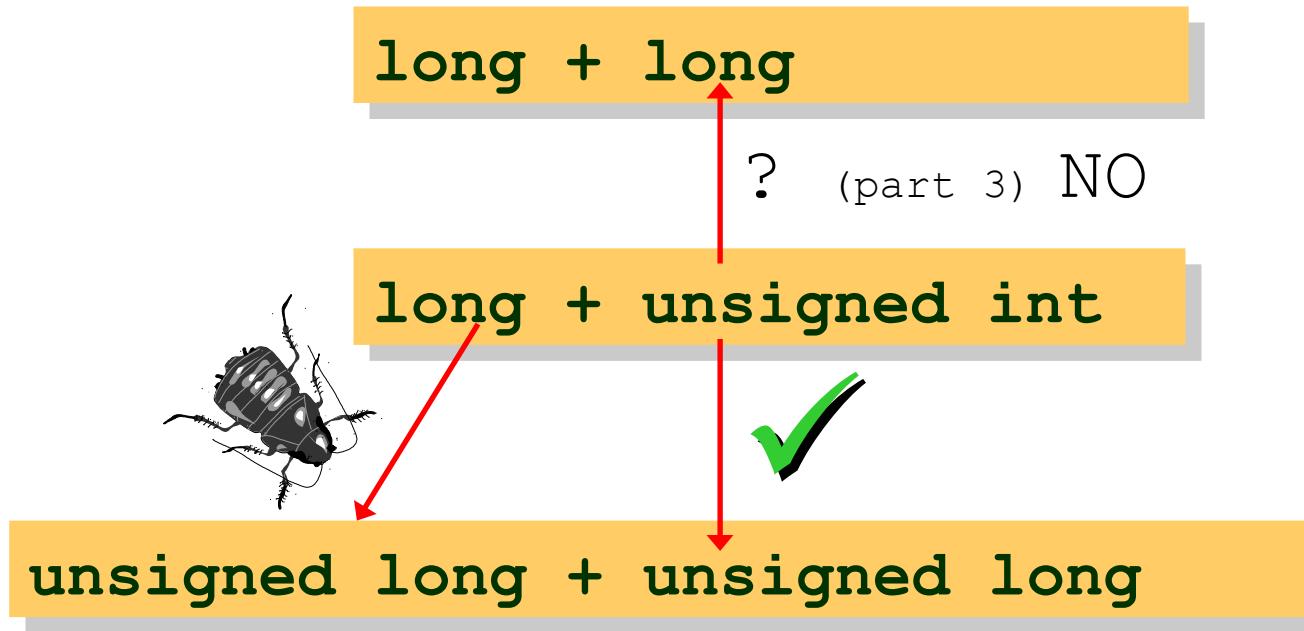
this depends on their value representations, as specified in <limits.h>

long + long

- 6.3.1.8 Usual arithmetic conversions
 - ◆ part 4 – the “last resort” rule (lossy)

...

- Otherwise, both operands are converted to the unsigned integer type corresponding to the type of the operand with signed integer type.



- is this program's behavior
 - ◊ undefined?
 - ◊ unspecified?
 - ◊ implementation-defined?
 - ◊ conforming?
 - ◊ strictly conforming?

```
#include <stdio.h>

int main(void)
{
    unsigned long a = 0;
    signed int b = -42;
    unsigned long long c = a + b;
    printf("%llu\n", c);
}
```



- **is this program's behavior**
 - ◊ **undefined?** NO
 - ◊ **unspecified?** NO
 - ◊ **implementation-defined?** YES
 - ◊ **conforming?** YES
 - ◊ **strictly conforming?** NO

```
#include <stdio.h>

int main(void)
{
    unsigned long a = 0;
    signed int b = -42;
    unsigned long long c = a + b;
    printf("%llu\n", c);
}
```

- 6.3.1.3 Signed and unsigned integers
 - ◆ para 1 – When a value with integer type is converted to another integer type, other than `_Bool`, if the value can be represented by the new type, it is unchanged.
 - ◆ para 2 – Otherwise, if the new type is unsigned, the value is converted by repeatedly adding or subtracting one more than the maximum value that can be represented in the new type until the value is in the range of the new type.
 - ◆ para 3 – Otherwise, the new type is signed and the value cannot be represented in it; either the result is implementation-defined or an implementation-defined signal is raised.

- these operators perform **no** conversions

unary	!	} → int 0/1	
boolean	&&		
unary	++ --		
assignment	= *= /= %= += -= ...		
comma	,		

- these operators perform **integer promotion**

unary	~ + -
shift	<< >>

- these operators perform the *usual arithmetic conversions*

conversions

arithmetic	* / % + -
relational	< > <= >= == !=
bitwise	& ^
ternary	? :

- what does this program print?

- ◆ assume `sizeof(short) == 2`
- ◆ assume `sizeof(int) == 4`

```
void exercise(void)
{
    short s = 42;

    printf("%zd\n", sizeof(s && s));
    printf("%zd\n", sizeof(s));
    printf("%zd\n", sizeof(+s));
    printf("%zd\n", sizeof(s = s));
}
```



```
void exercise(void)
{
    short s = 42;

    printf("%zd\n", sizeof(s && s));
    printf("%zd\n", sizeof(s));
    printf("%zd\n", sizeof(+s));
    printf("%zd\n", sizeof(s = s));
}
```

answer

→ 4 2 4 2

Concurrency

memory_order_seq_cst

```
int x = 0, y = 0;
```

Thread 1

```
r1 = load(y)
store(x, r1)
```

Thread 2

```
r2 = load(x)
store(y, 42)
```

T1 before T2

```
r1 = load(y)
store(x, r1)      r1 = 0
                  x = 0
```

```
r2 = load(x)
store(y, 42)      r2 = 0
                  y = 42
```

T2 before T1

```
r2 = load(x)
store(y, 42)      r2 = 0
                  y = 42
```

```
r1 = load(y)
store(x, r1)      r1 = 0
                  x = 0
```

T1 around T2

```
r1 = load(y)      r1 = 0
```

```
r2 = load(x)
store(y, 42)      r2 = 0
                  y = 42
```

```
store(x, r1)      x = 0
```

T2 around T1

```
r2 = load(x)      r2 = 0
```

```
r1 = load(y)
store(x, r1)      r1 = 0
                  x = 0
```

```
store(y, 42)      y = 42
```

```
int x = 0, y = 0;
```

Thread 1

```
r1 = load(y)  
store(x, r1)
```

Thread 2

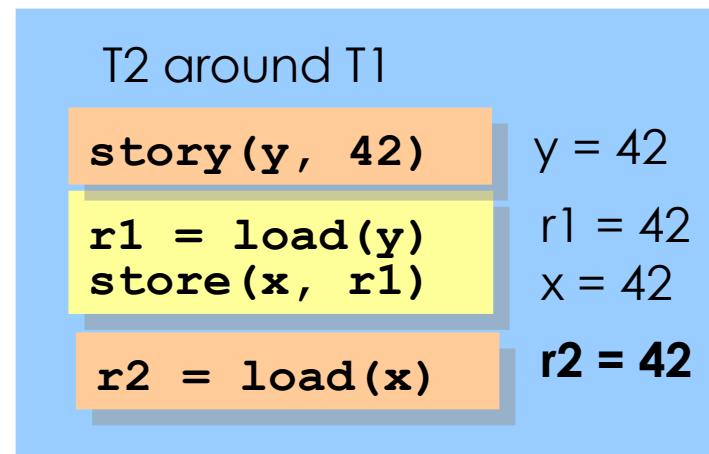
```
r2 = load(x)  
store(y, 42)
```



```
r1 = load(y)  
store(x, r1)
```

What if the implementation re-orders the expressions in Thread 2 ?

```
store(y, 42)  
r2 = load(x)
```



Is the implementation allowed to re-order like that? **YES!**

Only sequence points govern the order of evaluation in a single thread.

memory_order_seq_cst says operations on atomic types in a thread shall occur in a sequentially consistent order.

• 7.17 <stdatomic.h>

7.13.3 Order and consistency

The enumerated type `memory_order` specifies the detailed regular (non-atomic) memory synchronization operations as defined in 5.1.2.4...

`memory_order_relaxed`
`memory_order_consume`
`memory_order_acquire`
`memory_order_release`
`memory_order_acq_rel`
`memory_order_seq_cst`

For ... `memory_order_seq_cst`, a store operation performs a release operation on the affected memory location.

For ... `memory_order_seq_cst`, a load operation performs an acquire operation on the affected memory location.



- **6.7.2.4 Atomic type specifier**

- para 21 – An atomic type describes the type designated by the construct

_Atomic (type-name)



_Atomic is a keyword



_Atomic type-name
is also allowed. _Atomic is a
type qualifier (like const).

Atomic(int) x = 0, y = 0;

Thread 1

```
r1 = load(y)  
store(x, r1)
```

Thread 2

```
r2 = load(x)  
store(y, 42)
```



The implementation shall not re-order operations on x or y

```
r1 = load(y)  
store(x, r1)
```

```
r2 = load(x)  
store(y, 42)
```

T1 before T2

T2 before T1

T1 around T2

T2 around T1

y = 42
r1 = 0
x = 0
r2 = 0

• 7.17 <stdatomic.h>

7.17.6 Atomic integer types

For each line in the following table, the atomic type name is declared as a type that has the same representation and alignment requirements as the corresponding direct type.

<code>atomic_bool</code>	<code>_Atomic_Bool</code>
<code>atomic_char</code>	<code>_Atomic_char</code>
<code>atomic_schar</code>	<code>_Atomic_signed char</code>
<code>atomic_uchar</code>	<code>_Atomic_unsigned char</code>
<code>atomic_short</code>	<code>_Atomic_short</code>
<code>atomic_ushort</code>	<code>_Atomic_unsigned short</code>
<code>atomic_int</code>	<code>_Atomic_int</code>
<code>atomic_uint</code>	<code>_Atomic_unsigned int</code>
...	
...	
<code>atomic_size_t</code>	<code>_Atomic_size_t</code>
...	

- **7.17 <stdatomic.h>**

7.17.1 *Introduction*

Implementations that define the macro `_STD_NO_ATOMICS_` need not provide this header nor support any of its facilities.

The macros defined are the atomic lock-free macros

- `ATOMIC_BOOL_LOCK_FREE`
- `ATOMIC_CHAR_LOCK_FREE`
- `ATOMIC_CHAR16_T_LOCK_FREE`
- `ATOMIC_CHAR32_T_LOCK_FREE`
- `ATOMIC_WCHAR_T_LOCK_FREE`
- `ATOMIC_SHORT_LOCK_FREE`
- `ATOMIC_INT_LOCK_FREE`
- `ATOMIC_LONG_LOCK_FREE`
- `ATOMIC_LLONG_LOCK_FREE`
- `ATOMIC_POINTER_LOCK_FREE`

which indicate the lock-free property of the corresponding atomic types (both signed and unsigned)

```
#include <stdatomic.h>
atomic_int x = 0, y = 0;
```

Thread 1

```
r1 = load(y)
store(x, r1)
```

Thread 2

```
r2 = load(x)
store(y, 42)
```



```
r1 = load(y)
store(x, r1)
```

The implementation shall
not re-order operations
on x or y

```
r2 = load(x)
store(y, 42)
```

T1 before T2

T2 before T1

T1 around T2

T2 around T1

y = 42
r1 = 0
x = 0
r2 = 0

example

```
#include <stdatomic.h>
#include <stdio.h>
#include <threads.h>

atomic_int counter = 0;

static void f()
{
    for (int i = 0; i < 10000; i++)
    {
        counter++;
    }
}

int main()
{
    enum { num_threads = 1000 };
    thrd_t threads[num_threads];
    for (int i = 0; i < num_threads; i++)
    {
        thrd_create(&threads[i], f, &i);
    }
    for (int i = 0; i < num_threads; i++)
    {
        thrd_join(&threads[i], NULL);
    }
    printf("counter = %d\n", counter);
}
```

• 6.5.16.2 Compound assignment

- ♦ para 3 – E1 op= E2 If E1 has an *atomic type*, compound assignment is a read-modify-write operation with `memory_order_seq_cst` semantics.

```
atomic_int counter = 0;
```

```
counter += 42;
```

- 6.2.6.2 Integer types
 - ◆ para 9 – Loads and stores of objects with atomic types are done with `memory_order_seq_cst` semantics.
- 6.3.2.1 Lvalues, arrays & function designators
 - ◆ para 2 – ... Except when ... an lvalue ... is converted to the value stored in the designated object; this is called the lvalue conversion.
 - ◆ ... if the lvalue has atomic type, the value has the non atomic version of the type of the lvalue.

```
atomic_int counter = 0;  
int load, store;
```

```
load = counter;
```

```
counter = store;
```

- **6.5.2.4 Postfix increment and decrement**

- para 2 – postfix `++` on an object with atomic type is a read-modify-write operation with `memory_order_seq_cst` semantics.

```
atomic_int counter = 0;
```

```
counter ++;
```

- 6.5.2.3 Structure and union members

- ♦ para 5 – Accessing a member of an atomic structure or union results in undefined behavior.

```
struct date
{
    int year;
    int month;
    int day;
};
```

```
_Atomic struct date deadline;
```

```
struct date due = deadline;
due.day++;
deadline = due;
```

- 7.17.2.1 The ATOMIC_VAR_INIT macro
 - ◆ para 1 – The ATOMIC_VAR_INIT macro expands to a token sequence suitable for initializing an atomic object of a type that is initialization compatible...

```
#include <stdatomic.h>

_Atomic struct date deadline =
    ATOMIC_VAR_INIT((struct date) {
        .year = 2014,
        .month = 2,
        .day = 28
    });
}
```



ATOMIC_VAR_INIT itself is not thread safe

lost updates

```
_Atomic struct date deadline = ...;
```



```
struct date due;  
due = deadline;  
due.day++;
```

Thread 1



```
struct date due;  
due = deadline;  
due.day++;
```

Thread 2

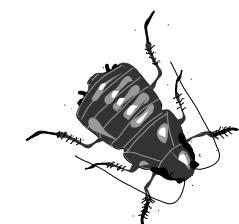


```
deadline = due;
```

Thread 1



```
deadline = due;
```



- 5.1.2.4 Multi-threaded execution
 - ◆ para 4 – Two expression evaluations conflict if one of them modifies a memory location and the other one reads or modifies the same memory location.
 - ◆ para 25 - The execution of a program contains a data race if it contains two conflicting actions in different threads, at least one of which is not atomic, and neither happens before the other. Any such data race results in undefined behavior.
 - ◆ para 18 – An evaluation A happens before an evaluation B if
 - A is sequenced before B or
 - A inter-thread happens before B

- 5.1.2.4 Multi-threaded execution
 - ◆ para 16 – An evaluation A inter-thread happens before an evaluation B if
 - A synchronizes with B,
 - A is dependency ordered before B, or
 - for some evaluation of X,
 - A synchronizes with X and X is sequenced before B,
 - A is sequenced before X and X inter-thread happens before B, or
 - A inter-thread happens before X and X inter-thread happens before B

- 5.1.2.4 Multi-threaded execution
 - ◆ para 5 – The library defines a number of atomic operations (7.17) and operations on mutexes (7.26.4) that are specially identified as synchronization operations.
 - ◆ These operations play a special role in making assignments in one thread visible to another.
 - ◆ A synchronization operation on one or more memory locations is either an acquire operation, a release operation, both an acquire and a release operation, or a consume operation.

- 7.26.4 <threads.h>
- Mutex functions

mtx_t is a complete object type that holds an identifier for a mutex.

```
void mtx_destroy(mtx_t * mtx);
int mtx_init(mtx_t * mtx, int type);
int mtx_lock(mtx_t * mtx);
int mtx_timedlock(mtx_t * restrict mtx,
                  const struct timespec * restrict ts);
int mtx_trylock(mtx_t * mtx);
int mtx_unlock(mtx_t * mtx);
```

found updates

```
#include <threads.h>

_Atomic struct date deadline = ...;

→ mtx_t key;

int main(void)
{
    → mtx_init(&key, mtx_plain);
        // start two threads
        // join with two threads
    → mtx_destroy(&key);
}
```

found updates

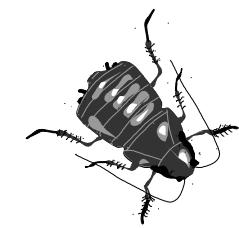
Thread 2

```
struct date due;  
mtx_lock(&key);  
due = deadline;  
due.day++;  
deadline = due;  
mtx_unlock(&key);
```



Thread 1

```
struct date due;  
mtx_lock(&key);  
due = deadline;  
due.day++;  
deadline = due;  
mtx_unlock(&key);
```



excessive locking

Thread 2

```
struct date due;  
mtx_lock(&key);  
due = deadline;◄  
due.day++;  
deadline = due;◄  
mtx_unlock(&key);
```



Thread 1

```
struct date due;  
mtx_lock(&key);  
due = deadline;◄  
due.day++;  
deadline = due;◄  
mtx_unlock(&key);
```



```
#include <threads.h>

→ struct date deadline = ... ;
      mtx_t key;

int main(void)
{
    // start two threads
    // join with two threads
}
```



```
    {  
        mtx_lock(&key);  
        deadline.day++;  
        mtx_unlock(&key);  
    }
```

Thread 2



```
    {  
        mtx_lock(&key);  
        deadline.day++;  
        mtx_unlock(&key);  
    }
```

Thread 1

- 7.26.5 <threads.h>
- Thread functions

thrd_t is a complete object type that holds an identifier for a thread.

<threads.h>

```
int thrd_create(thrd_t * thr, thrd_start_t func, void * arg);
thrd_t thrd_current(void);
int thrd_detach(thrd_t thr);
int thrd_equal(thrd_t thr0, thrd_t thr1);
_Noreturn void thrd_exit(int res);
int thrd_join(thrd_t thr, int * res);
int thrd_sleep(const struct timespec * duration,
               struct timespec * remaining);
void thrd_yield(void);
```

- 7.26.3 <threads.h>
- Condition variable functions

cnd_t is a complete object type that holds an identifier for a condition variable.

```
int cnd_broadcast(cnd_t * cond);
void cnd_destroy(cnd_t * cond);
int cnd_init(cnd_t * cond);
int cnd_signal(cnd_t * cond);
int cnd_timedwait(cnd_t * restrict cond,
                  mtx_t * restrict mtx,
                  const struct timespec * restrict ts);
int cnd_wait(cnd_t * cond, mtx_t * mtx);
```

- 7.26.6 <threads.h>
- Thread-specific storage functions

tss_t is a complete object type that holds an identifier for a thread-specific storage pointer.

```
int tss_create(tss_t * key, tss_dtor_t dtor);
void tss_delete(tss_t key);
void * tss_get(tss_t key);
int tss_set(tss_t key, void * val);
```

- **The C Programming Language**
 - ◆ Kernighan and Ritchie
- **The C Standard**
 - ◆ BSI
- **C: A Reference Manual**
 - ◆ Harbison and Steele
- **C FAQ's**
 - ◆ Steve Summit
- **Expert C Programming**
 - ◆ Peter van der Linden
- **Safer C**
 - ◆ Les Hatton
- **The Standard C Library**
 - ◆ P.J.Plauger

chapter and verse!



Unit Testing

what is a unit?

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- A Unit Test is
 - ◆ Isolated – it has no external dependencies
 - it passes or fails solely due to the test code and the code under test
 - ◆ Repeatable
 - No external dependencies means if it passed last time and the code hasn't changed it will pass this time
 - ◆ Automatable
 - No external dependencies means it can run all by itself
 - ◆ Fast
 - No external dependencies means nothing external is slowing the test execution down

- How to unit test one function...

testability



example.c

```
#include <stdio.h>
...
void not_easily(void)
{
    fputc('4', stdout);
    fputc('2', stdout);
}
```

<stdio.h>

```
...
FILE * stdout = ...;

int fputc(int c, FILE * f)
{
    ...
}
```

- Move the function definition into its own file...
 - ◆ Include this file from where it used to live

step 1



example.c

```
#include <stdio.h>
...
#include "not_easily.func"
```

not_easily.func

```
void not_easily(void)
{
    fputc('4', stdout);
    fputc('2', stdout);
}
```

- **Include the source in the test**

not_easily.tests.c

```
#include <assert.h>

...
#include "not_easily.func"

void not_easily_tests(void)
{
    not_easily();
}
```

step 2



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- Create a mock environment

not_easily.tests.c

```
#include <assert.h>

typedef int mock_file;

static mock_file * stdout = 0;

static int fputc(int c, mock_file * f)
{
    ...
}

#include "not_easily.func"

void not_easily_tests(void)
{
    not_easily();
}
```

step 3



- Test from within the mock environment

not_easily.tests.c

```
#include <assert.h>

typedef int mock_file;

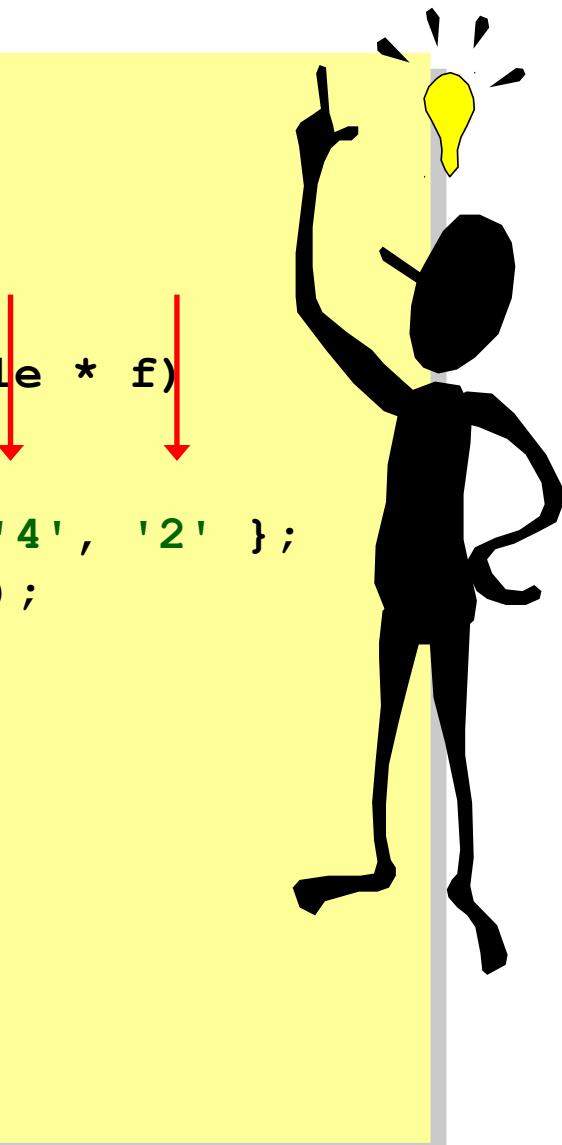
static mock_file * stdout = 0;

static int fputc(int c, mock_file * f)
{
    static int count = 0;
    static int expected[2] = { '4', '2' };
    assert(expected[count] == c);
    count = (count + 1) % 2;
    ...
}

#include "not_easily.func"

void not_easily_tests(void)
{
    not_easily();
}
```

step 4



- Write a simple utility to read given lines (eg 311-355) from a named file and save these lines to a new file as part of the test build
 - ◆ Simple verification is probably good enough
 - First line contains the named function
 - Last line contains only a }
- Include this made file from the source instead of including the .func file
 - ◆ This way leaves the original source file completely intact

get_lines.rb

```
lines = STDIN.readlines
start = ARGV[0].to_i - 1
finish = ARGV[1].to_i - 1
STDOUT.write lines[start..finish]
```

for example

- How to unit test dependent functions?

testability



example.c

```
#include "local.h"
#include <string.h>
#include <stdio.h>
...
int b(int value)
{
}

int c(int value)
{
}

int a(int value)
{
    return b(value) + c(value);
}
```

- Do includes indirectly

step 1



```
#define LOCAL(x) #x  
#define SYSTEM(x) <x>
```

example.c

```
#include LOCAL(local.h)  
#include SYSTEM(string.h)  
#include SYSTEM(stdio.h)  
  
...  
  
int a(int value)  
{  
    return b(value) + c(value);  
}
```

- **Divert includes when unit-testing**

step 2



```
#ifdef UNIT_TESTING
#  define LOCAL(x) "mock/" ## #x
#  define SYSTEM(x) LOCAL(x)

#else
#  define LOCAL(x) #x
#  define SYSTEM(x) <x>

#endif
```



- Include the source in the test

step 3



example.tests.c

```
#include <assert.h>

#define UNIT_TESTING
#include "example.c" ←

void example_test(void)
{
    assert(3 == a(42));
    ...
}
```

- Create a mock environment



specific/mock/stdio.h

```
typedef int mock_file;  
  
static mock_file * stdout = 0;  
  
int fputc(int c, mock_file * f)  
{  
    ...  
}
```

specific/mock/string.h

```
int strcmp(const char * lhs, const char * rhs)  
{  
    ...  
}
```

specific/mock/local.h

```
...
```

- Test from within the mock environment

step 5

specific/mock/stdio.h

```
typedef int mock_file;  
  
static mock_file * stdout = 0;  
  
int fputc(int c, mock_file * f)  
{  
    → assert(...);  
}
```

specific/mock/string.h

```
int strcmp(const char * lhs, const char * rhs)  
{  
    → assert(...);  
}
```

- Write a simple utility copying input to new output file, except includes are commented
 - ◆ `#include "abc.h"` → `/* #include "abc.h" */`
 - ◆ `#include <def.h>` → `/* #include <def.h> */`
- Include this generated file in the test file
 - ◆ This leaves the original source file completely intact
 - ◆ This way all mock functions, mock data, and mock types can live inside the one test file

for example

excluder.rb

```
include  = Regexp.new(' (\s*)#(\s*)include(.* ) ')
```

```
STDIN.readlines.each do |line|
  if m = include.match(line)
    line = "#if 0\n" + line + "#endif\n"
  end
  STDOUT.write line
end
```

```
cat wibble.c | ruby excluder.rb > wibble.isolated.c
```

wibble.tests.c

```
... ←  
#include "wibble.isolated.c"  
  
void wibble_tests(void)  
{  
  ...  
}
```

mock environment

impossible?

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- Code that is impossible to unit-test...
- Is not impossible to test
- It might be hard to unit test
- It might be awkward to unit test
- It might be messy to unit test
- But it will be possible

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- How hard are you willing to try?
- Only when you try will you find out...
- What makes code easy to unit test
- What makes code hard to unit test
- What tangled dependencies most code has

ask yourself...

- Writing unit tests takes effort
 - ◆ At first this effort is new and frightening
- That effort is rewarded many times over
 - ◆ It's never as bad as you think anyway
- Unit tests help you to write better code
 - ◆ You get better over time
- Unit tests create confidence to refactor
 - ◆ The codebase gets better over time
- Unit tests improve productivity
 - ◆ Why do cars have brakes?



...

Michael Feathers
Working Effectively With Legacy Code

Legacy code is code that has no tests.

A unit test that takes 1/10th of a second to run is a slow unit test.

Characterisation tests...

- Advice on test output

⋮