Building Multi-File Programs with the `make` Tool

Agenda

Motivation for Make

Make Fundamentals

Non-File Targets

Macros

Multi-File Programs

intmath.h (interface)

```
#ifndef INTMATH_INCLUDED
#define INTMATH_INCLUDED
int gcd(int i, int j);
int lcm(int i, int j);
#endif
```

intmath.c (implementation)

```
#include "intmath.h"

int gcd(int i, int j)
{  int temp;
   while (j != 0)
   { temp = i % j;
     i = j;
     j = temp;
   }
   return i;
}

int lcm(int i, int j)
{  return (i / gcd(i, j)) * j;
}
```

testintmath.c (client)

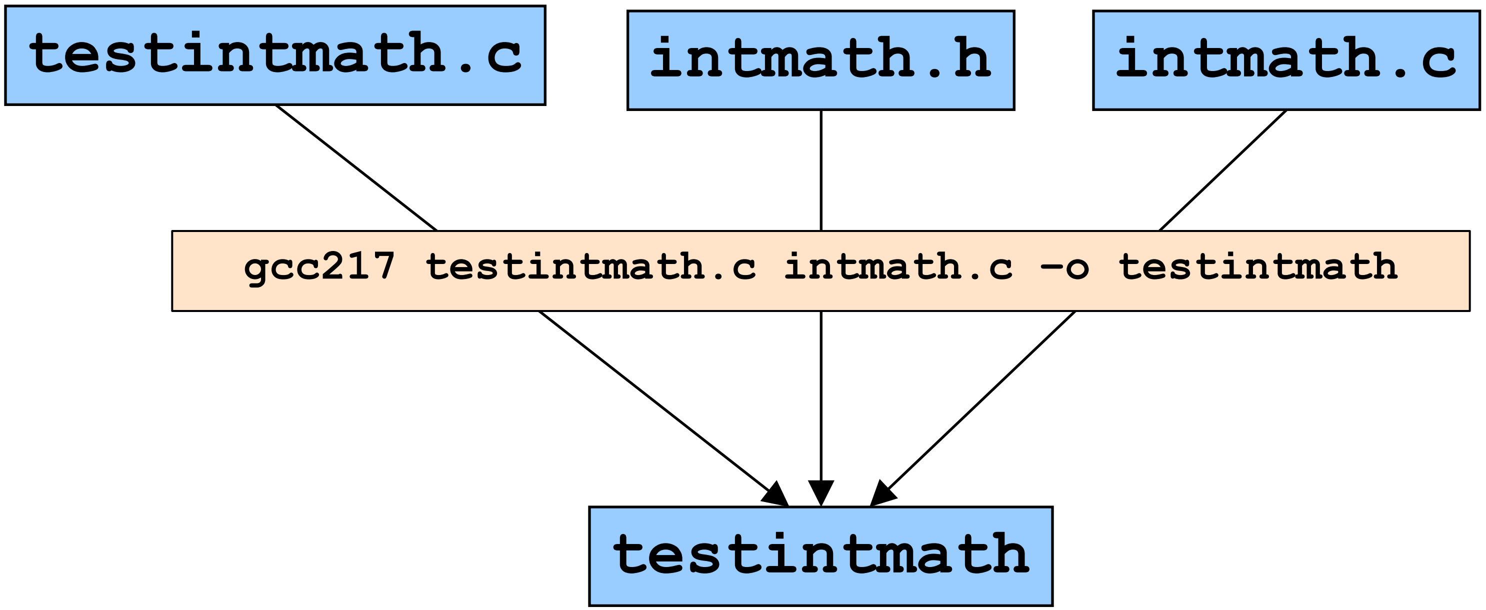
```
#include "intmath.h"
#include <stdio.h>

int main(void)
{  int i;
   int j;
   printf("Enter the first integer:\n");
   scanf("%d", &i);
   printf("Enter the second integer:\n");
   scanf("%d", &j);
   printf("Greatest common divisor: %d.\n",
      gcd(i, j));
   printf("Least common multiple: %d.\n",
      lcm(i, j);
   return 0;
}
```

Note: intmath.h is #included into intmath.c and testintmath.c

Motivation for Make (Part 1)

Building **`testintmath`**, approach 1:

- Use one **`gcc217`** command to preprocess, compile, assemble, and link



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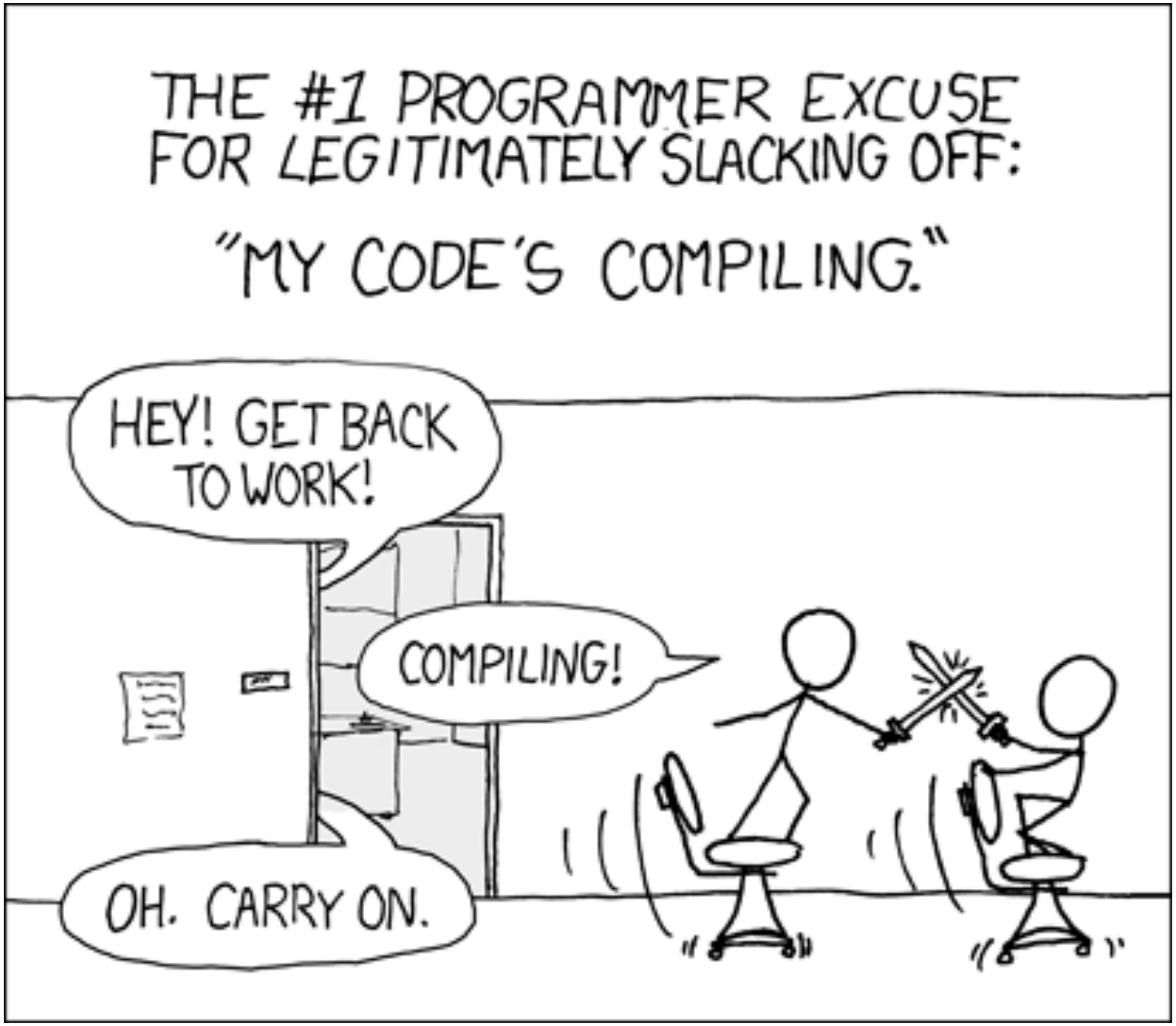
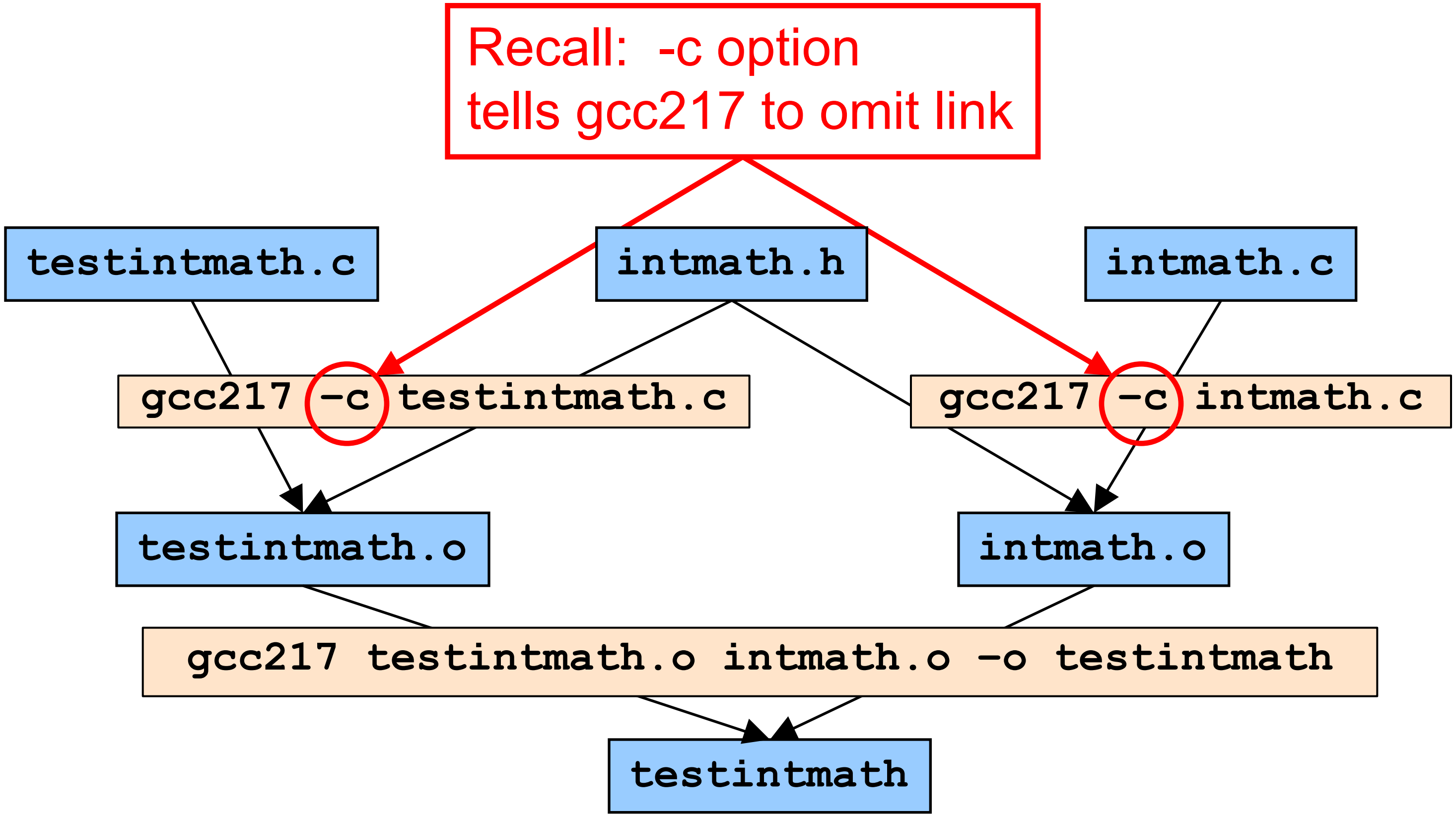


Motivation for Make (Part 2)

Building **testintmath**, approach 2:

- Preprocess, compile, assemble to produce .o files
- Link to produce executable binary file

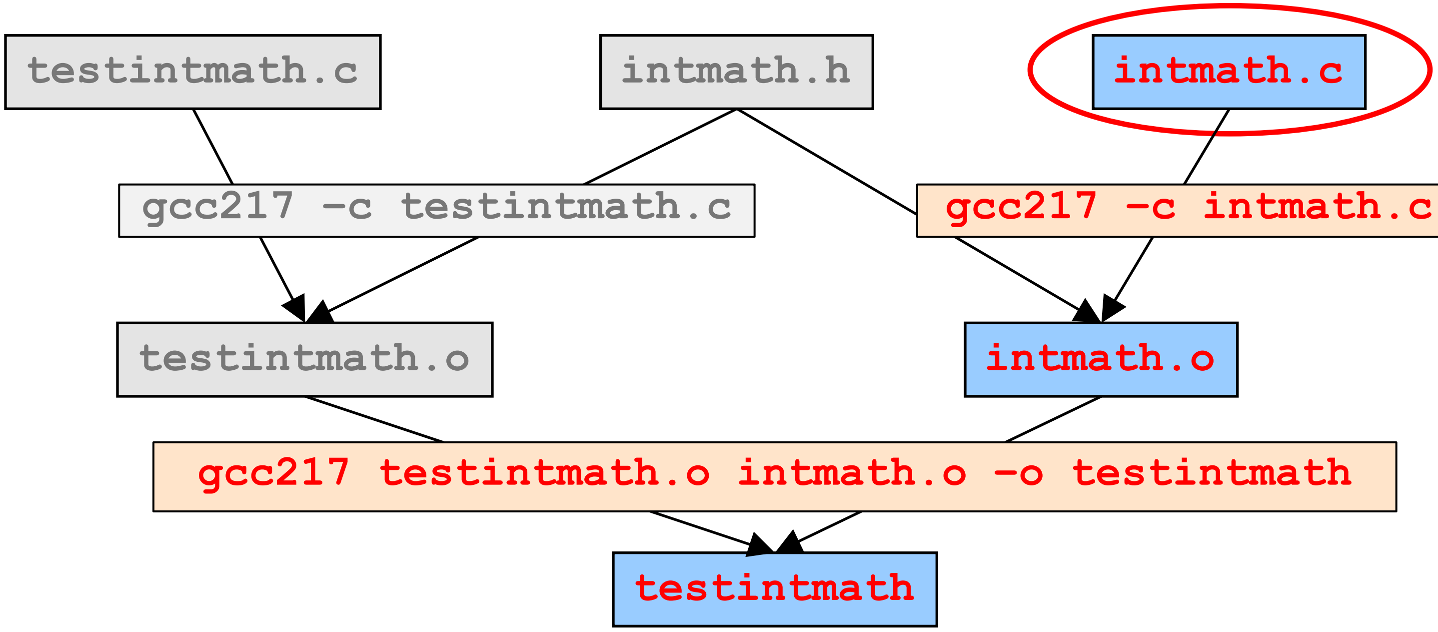


Partial Builds

Approach 2 allows for **partial builds**

- Example: Change **`intmath.c`**
  - Must rebuild **`intmath.o`** and **`testintmath`**
  - Need not rebuild **`testintmath.o`**

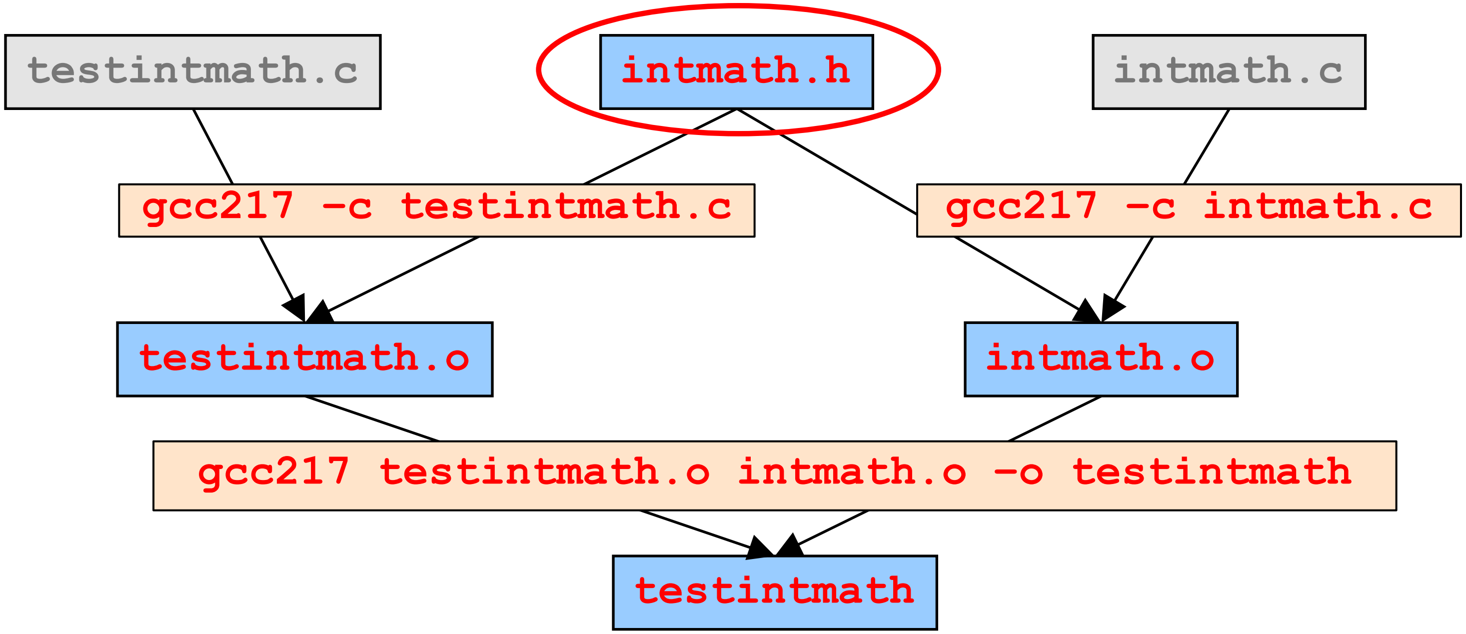
If program contains many files, could save many hours of build time



Partial Builds

However, changing a .h file can be more dramatic

- Example: Change **`intmath.h`**
  - **`intmath.h`** is #included into **`testintmath.c`** and **`intmath.c`**
  - Must rebuild **`testintmath.o`**, **`intmath.o`**, and **`testintmath`**



Wouldn't It Be Nice If…

Observation

- Doing partial builds manually is tedious and error-prone
- Wouldn't it be nice if there were a tool…

How would the tool work?

- Input:
  - Dependency graph (as shown previously)
    - Specifies file dependencies
    - Specifies commands to build each file from its dependents
  - Date/time stamps of files
- Algorithm:
  - ***If*** file B depends on A ***and***
    date/time stamp of A is newer than date/time stamp of B,
    then rebuild B using the specified command

That's `make`!

Agenda

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Make Command Syntax

Command syntax

```
$ man make
SYNOPSIS
    make [-f makefile] [options] [targets]
```

- ***makefile***
  - Textual representation of dependency graph
  - Contains **dependency rules**
  - Default name is **`makefile`**, then **`Makefile`**
- ***target***
  - What **`make`** should build
  - Usually: .o file, or an executable binary file
  - Default is first one defined in ***makefile***

Dependency Rules in Makefile

Dependency rule syntax

```
target: prerequisites
    <tab>command
```

- ***target***: the file you want to build
- ***dependencies (aka prerequisites)***:
  the files needed to build the target
- ***command***: what to execute to build the target

Dependency rule semantics

- Build ***target*** iff it is older than any of its ***dependencies***
- Use ***command*** to do the build

Work recursively; examples illustrate…

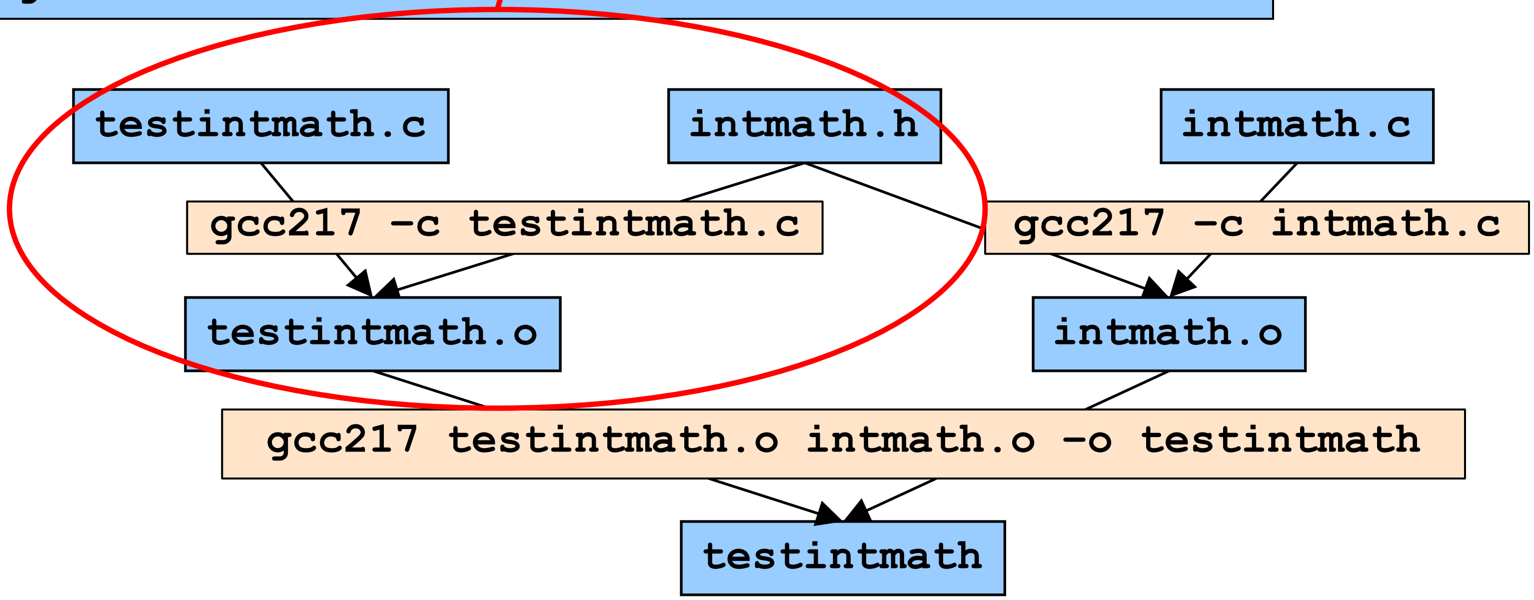
Makefile Version 1

Makefile:

```
testintmath: testintmath.o intmath.o
	gcc217 testintmath.o intmath.o -o testintmath

testintmath.o: testintmath.c intmath.h
	gcc217 -c testintmath.c

intmath.o: intmath.c intmath.h
	gcc217 -c intmath.c
```



Version 1 in Action

At first, to build testintmath make issues all three gcc commands

Use the touch command to change the date/time stamp of intmath.c

```
$ make testintmath
gcc217 -c testintmath.c
gcc217 -c intmath.c
gcc217 testintmath.o intmath.o -o testintmath

$ touch intmath.c

$ make testintmath
gcc217 -c intmath.c
gcc217 testintmath.o intmath.o -o testintmath

$ make testintmath
make: `testintmath' is up to date.

$ make
make: `testintmath' is up to date.
```

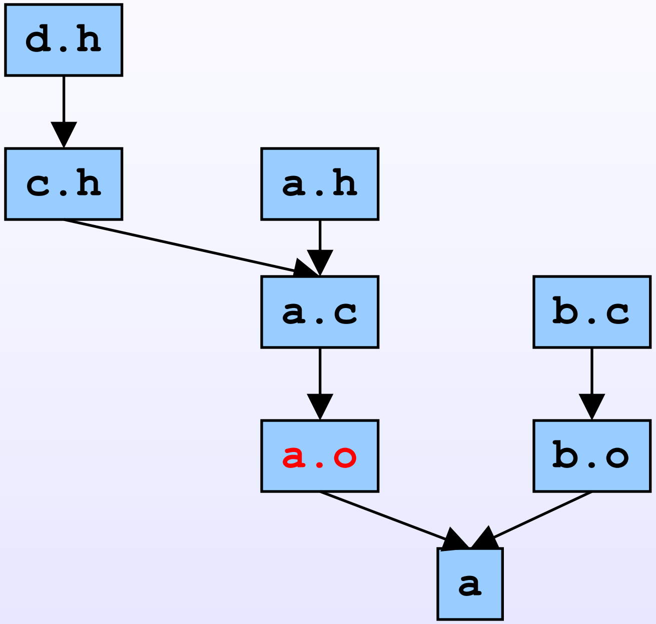
make does a partial build

make notes that the specified target is up to date

The default target is testintmath, the target of the first dependency rule

iClicker Question

Q: If you were making a **`Makefile`** for this program, what should **`a.o`** depend on?



A. **`a`**

B. **`a.c`**

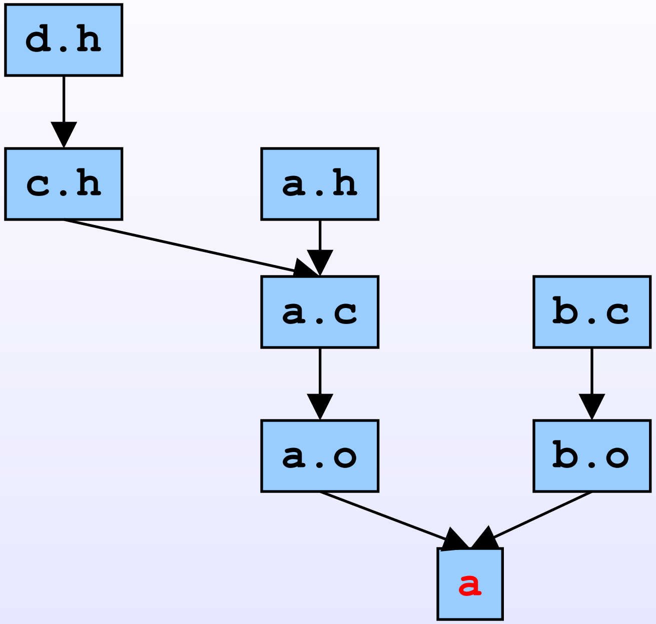
C. **`a.c a.h`**

D. **`a.h c.h d.h`**

E. **`a.c a.h c.h d.h`**

iClicker Question

Q: If you were making a **`Makefile`** for this program, what should **`a`** depend on?



A. **`a.o b.o`**

B. **`a.o b.o a.c b.c`**

C. **`a.o b.o a.h c.h d.h`**

D. **`a.c b.c a.h c.h d.h`**

E. **`a.o b.o a.c b.c a.h c.h d.h`**

Agenda

Motivation for Make

Make Fundamentals

Non-File Targets

Macros

Non-File Targets

Adding useful shortcuts for the programmer

- **make all**: create the final executable binary file(s)
- **make clean**: delete all .o files, executable binary file(s)
- **make clobber**: delete all Emacs backup files, all .o files, executable(s)

Commands in the example

- **rm -f**: remove files without querying the user
- Files ending in '**~**' and starting/ending in '**#**' are Emacs special files

```
all: testintmath

clobber: clean
    rm -f *~ \#*\#

clean:
    rm -f testintmath *.o
```

Makefile Version 2

```
# Dependency rules for non-file targets
all: testintmath
clobber: clean
  rm -f *~ \#*\#
clean:
  rm -f testintmath *.o

# Dependency rules for file targets
testintmath: testintmath.o intmath.o
  gcc217 testintmath.o intmath.o –o testintmath
testintmath.o: testintmath.c intmath.h
  gcc217 -c testintmath.c
intmath.o: intmath.c intmath.h
  gcc217 -c intmath.c
```

Version 2 in Action

make observes that "clean" target doesn't exist; attempts to build it by issuing "rm" command

```
$ make clean
rm -f testintmath *.o
```

```
$ make clobber
rm -f testintmath *.o
rm -f *~ \#*\#
```

```
$ make all
gcc217 -c testintmath.c
gcc217 -c intmath.c
gcc217 testintmath.o intmath.o -o testintmath
```

```
$ make
make: Nothing to be done for `all'.
```

Same idea here, but "clobber" depends upon "clean"

"all" depends upon "testintmath"

"all" is the default target

Agenda

Motivation for Make

Make Fundamentals

Non-File Targets

Macros

Macros

make has a macro facility

- Performs textual substitution
- Similar to C preprocessor's **#define**

Macro definition syntax

macroname* = *macrodefinition

- **make** replaces ***$(macroname)*** with ***macrodefinition*** in remainder of Makefile

Example: Make it easy to change (or swap) build commands

```
CC = gcc217#m
YACC = bison -d -y
#YACC = yacc -d
```

Example: Make it easy to change build flags

```
CFLAGS = -D NDEBUG -O
```

Makefile Version 3

```
# Macros
CC = gcc217
# CC = gcc217m
CFLAGS =
# CFLAGS = -g
# CFLAGS = -D NDEBUG
# CFLAGS = -D NDEBUG -O

# Dependency rules for non-file targets
all: testintmath
clobber: clean
	rm -f *~ \#*\#
clean:
	rm -f testintmath *.o

# Dependency rules for file targets
testintmath: testintmath.o intmath.o
	$(CC) $(CFLAGS) testintmath.o intmath.o -o testintmath
testintmath.o: testintmath.c intmath.h
	$(CC) $(CFLAGS) -c testintmath.c
intmath.o: intmath.c intmath.h
	$(CC) $(CFLAGS) -c intmath.c
```

Version 3 in Action

Same as Version 2

Makefile Gotchas

Beware:

- Each command (i.e., second line of each dependency rule) must begin with a tab character, not spaces
- Use the **`rm -f`** command with caution

Making Makefiles

In this course

- Create Makefiles manually

Beyond this course

- Can use tools to generate Makefiles
    - See **`mkmf`**, others

Advanced: Automatic Variables

`make` has wildcard matching for generalizing rules

- **`make`** has “pattern” rules that use % in targets and dependencies
- **`make`** has variables to fill in the ”pattern” in commands
  - **`$@`** : the target of the rule that was triggered
  - **`$<`** : the first dependency of the rule
  - **`$?`** : all the dependencies that are newer than the target
  - **`$^`** : all the dependencies

Examples:

```
testintmath: testintmath.o intmath.o
	$(CC) $(CFLAGS) $^ -o $@
%.o: %.c intmath.h
	$(CC) $(CFLAGS) -c $<
```

Not required (and potentially confusing!), but common.

Advanced: Implicit Rules

`make` has implicit rules for compiling and linking C programs

- **`make`** knows how to build x.o from x.c
  - Automatically uses $(CC) and $(CFLAGS)
- **`make`** knows how to build an executable from .o files
  - Automatically uses $(CC)

`make` has implicit rules for inferring dependencies

- **`make`** will assume that x.o depends upon x.c

Not required (and potentially confusing):
see appendix of these slides for details!

Make Resources

C Programming: A Modern Approach (King) Section 15.4

GNU make

- http://www.gnu.org/software/make/manual/make.html

Summary

Motivation for Make

- Automation of partial builds

Make fundamentals (Makefile version 1)

- Dependency rules, targets, dependencies, commands

Non-file targets (Makefile version 2)

Macros (Makefile version 3)

Debugging (Part 1)

The material for this lecture is drawn, in part, from
The Practice of Programming (Kernighan & Pike) Chapter 5

Goals of this Lecture

Help you learn about:

- Strategies and tools for debugging your code

Why?

- Debugging large programs can be difficult
- A power programmer knows a wide variety of debugging **strategies**
- A power programmer knows about **tools** that facilitate debugging
    - Debuggers
    - Version control systems

Testing vs. Debugging

Testing

- What should I do to try to **break** my program?

Debugging

- What should I do to try to **fix** my program?

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for familiar bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

(8) Focus on recent changes

Understand Error Messages

Debugging at **build-time** is easier than debugging at **run-time**, if and only if you…

Understand the error messages!

```
#include <stdioo.h>
/* Print "hello, world" to stdout and
   return 0.
int main(void)
{  printf("hello, world\n");
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdioo.h>
/* Print "hello, world" to stdout and
   return 0.
int main(void)
{  printf("hello, world\n");
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error(s)?

```
$ gcc217 hello.c -o hello
hello.c:1:20: error: stdioo.h: No such file or
directory
hello.c:2:1: error: unterminated comment
```

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  printf("hello, world\n")
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  printf("hello, world\n")
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error?

```
$ gcc217 hello.c -o hello
hello.c: In function 'main':
hello.c:6:4: error: expected ';' before 'return'
hello.c:7:1: warning: control reaches end of non-void
function
```

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  prinf("hello, world\n");
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  prinf("hello, world\n")
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error?

```
$ gcc217 hello.c -o hello
hello.c: In function 'main':
hello.c:5:1: warning: implicit declaration of function
'prinf'
/tmp/ccLSPMTR.o: In function `main':
hello.c:(.text+0x10): undefined reference to `prinf'
collect2: ld returned 1 exit status
```

Understand Error Messages

```
#include <stdio.h>
#include <stdlib.h>
int main(void)
{   enum StateType
    {   STATE_REGULAR,
        STATE_INWORD
    }
    printf("just hanging around\n");
    return EXIT_SUCCESS;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
#include <stdlib.h>
int main(void)
{  enum StateType
   {  STATE_REGULAR,
      STATE_INWORD
   }
   printf("just hanging around\n");
   return EXIT_SUCCESS;
}
```

What does this error message even mean?

```
$ gcc217 hello.c -o hello
hello.c:9:11: error: expected declaration specifiers or '...'
before string constant
```

Understand Error Messages

Caveats concerning error messages

- Line # in error message may be approximate
- Error message may seem nonsensical
- Compiler may not report the real error

Tips for eliminating error messages

- Clarity facilitates debugging
  - Make sure code is indented properly
- Look for missing “punctuation”
  - ; at ends of structure and enum type definitions
  - ; at ends of function declarations
  - ; at ends of do-while loops
- Work incrementally
  - Start at first error message
  - Fix, rebuild, repeat

Agenda

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Think Before Writing

Inappropriate changes could make matters worse, so…

Think before changing your code

- Explain the code to:
  - Yourself
  - Someone else
  - A Teddy bear / plushie stuffed tiger?
- Do experiments
  - But make sure they're disciplined

Agenda

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Look for Common Bugs

Some of our favorites:

```
switch (i)
{   case 0:
        …
        break;
    case 1:
        …
    case 2:
        …
}
```

```
int i;
…
scanf("%d", i);
```

```
char c;
…
c = getchar();
```

```
while (c = getchar() != EOF)
    …
```

```
if (i = 5)
    …
```

```
if (5 < i < 10)
    …
```

```
if (i & j)
    …
```

What are the errors?

Look for Common Bugs

Some of our favorites:

```
for (i = 0; i < 10; i++)
{   for (j = 0; j < 10; i++)
    {   ...
    }
}
```

```
for (i = 0; i < 10; i++)
{   for (j = 10; j >= 0; j++)
    {   ...
    }
}
```

What are the errors?

Look for Common Bugs

Some of our favorites:

```
{   int i;
    …
    i = 5;
    if (something)
    {   int i;
        …
        i = 6;
        …
    }
    …
    printf("%d\n", i);
    …
}
```

What value is written if this statement is present? Absent?

Agenda

(1) Understand error messages

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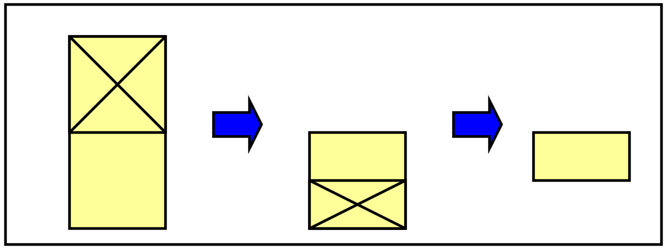
Divide and Conquer

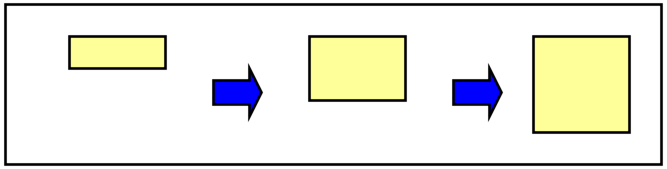
Divide and conquer: To debug a **program**…

- Incrementally find smallest **input file** that illustrates the bug

- Approach 1: **Remove** input
  - Start with file
  - Incrementally remove lines until bug disappears
  - Examine most-recently-removed lines



- Approach 2: **Add** input
  - Start with small subset of file
  - Incrementally add lines until bug appears
  - Examine most-recently-added lines



Divide and Conquer

Divide and conquer: To debug a **module**…

- Incrementally find smallest **client subset** that illustrates the bug

- Approach 1: **Remove** code
  - Start with test client
  - Incrementally remove lines of code until bug disappears
  - Examine most-recently-removed lines

- Approach 2: **Add** code
  - Start with minimal client
  - Incrementally add lines of test client until bug appears
  - Examine most-recently-added lines

Agenda

(1) Understand error messages

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Add More Internal Tests

(5) Add more internal tests

- Internal tests help **find** bugs (see “Testing” lecture)
- Internal test also can help **eliminate** bugs
  - Validating parameters & checking invariants can eliminate some functions from the bug hunt

Agenda

(1) Understand error messages

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Display Output

Write values of important variables at critical spots

- Poor:

```
printf("%d", keyvariable);
```

stdout is buffered; program may crash before output appears

- Maybe better:

```
printf("%d\n", keyvariable);
```

Printing **'\n'** flushes the **stdout** buffer, but not if **stdout** is redirected to a file

- Better:

```
printf("%d", keyvariable);
fflush(stdout);
```

Call **fflush()** to flush **stdout** buffer explicitly

Display Output

- Maybe even better:

```
fprintf(stderr, "%d", keyvariable);
```

Write debugging output to **`stderr`**; debugging output can be separated from normal output via redirection

Bonus: **`stderr`** is unbuffered

- Maybe better still:

```
FILE *fp = fopen("logfile", "w");
…
fprintf(fp, "%d", keyvariable);
fflush(fp);
```

Write to a log file

Agenda

(1) Understand error messages

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Use a Debugger

Use a debugger

- Alternative to displaying output

The GDB Debugger

GNU Debugger

- Part of the GNU development environment
- Integrated with Emacs editor
- Allows user to:
  - Run program
  - Set breakpoints
  - Step through code one line at a time
  - Examine values of variables during run
  - Etc.

For details see precept tutorial, precept reference sheet, Appendix 2 of these slides

Agenda

(1) Understand error messages

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Focus on Recent Changes

Focus on recent changes

- Corollary: Debug now, not later

Difficult:	Easier:
(1) Compose entire program	(1) Compose a little
(2) Test entire program	(2) Test a little
(3) Debug entire program	(3) Debug a little
	(4) Compose a little
	(5) Test a little
	(6) Debug a little
	…

Focus on Recent Changes

Focus on recent change (cont.)

- Corollary: Maintain old versions

Difficult:	Easier:
(1) Change code (2) Note new bug (3) Try to remember what changed since last version	(1) Backup current version (2) Change code (3) Note new bug (4) Compare code with last version to determine what changed

Maintaining Old Versions

To maintain old versions…

Approach 1: Manually copy project directory

```
…
$ mkdir myproject
$ cd myproject

   Create project files here.

$ cd ..
$ cp –r myproject myprojectDateTime
$ cd myproject

   Continue creating project files here.
…
```

Maintaining Old Versions

Approach 2: Use a **Revision Control System** such as subversion or git

- Allows programmer to:
  - **Check-in** source code files from **working copy** to **repository**
  - **Commit** revisions from **working copy** to **repository**
    - saves all old versions
  - **Update** source code files from **repository** to **working copy**
    - Can retrieve old versions
- Appropriate for one-developer projects
- Extremely useful, almost *necessary* for multideveloper projects!

Not required for COS 217, but good to know!

Google “subversion svn” or “git” for more information.

Summary

General debugging strategies and tools:

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

- Use GDB!!!

(8) Focus on recent changes

- Consider using git, etc.

Appendix 1: Implicit Rules

`make` has implicit rules for compiling and linking C programs

- **`make`** knows how to build x.o from x.c
  - Automatically uses $(CC) and $(CFLAGS)
- **`make`** knows how to build an executable from .o files
  - Automatically uses $(CC)

```
intmath.o: intmath.c intmath.h
	$(CC) $(CFLAGS) -c intmath.c
```

```
intmath.o: intmath.c intmath.h
```

```
testintmath: testintmath.o intmath.o
	$(CC) testintmath.o intmath.o -o testintmath
```

```
testintmath: testintmath.o intmath.o
```

Makefile Version 4

```
# Macros
CC = gcc217
# CC = gcc217m
CFLAGS =
# CFLAGS = -g
# CFLAGS = -D NDEBUG
# CFLAGS = -D NDEBUG -O

# Dependency rules for non-file targets
all: testintmath
clobber: clean
	rm -f *~ \#*\#
clean:
	rm -f testintmath *.o

# Dependency rules for file targets
testintmath: testintmath.o intmath.o
testintmath.o: testintmath.c intmath.h
intmath.o: intmath.c intmath.h
```

Version 4 in Action

Same as Version 2

Implicit Dependencies

`make` has implicit rules for inferring dependencies

- **`make`** will assume that x.o depends upon x.c

```
intmath.o: intmath.c intmath.h
```

```
intmath.o: intmath.h
```

Makefile Version 5

```
# Macros
CC = gcc217
# CC = gcc217m
CFLAGS =
# CFLAGS = -g
# CFLAGS = -D NDEBUG
# CFLAGS = -D NDEBUG -O

# Dependency rules for non-file targets
all: testintmath
clobber: clean
	rm -f *~ \#*\#
clean:
	rm -f testintmath *.o

# Dependency rules for file targets
testintmath: testintmath.o intmath.o
testintmath.o: intmath.h
intmath.o: intmath.h
```

Version 5 in Action

Same as Version 2

Makefile Gotchas

Beware:

- To use an implicit rule to make an *executable*, the executable must have the same name as one of the .o files

Correct:

```
myprog: myprog.o someotherfile.o
```

✓

Won't work:

```
myprog: somefile.o someotherfile.o
```

✗

Appendix 2: Using GDB

An example program

File testintmath.c:

Euclid's algorithm;
Don't be concerned
with details

```
#include <stdio.h>

int gcd(int i, int j)
{   int temp;
    while (j != 0)
    {   temp = i % j;
        i = j;
        j = temp;
    }
    return i;
}

int lcm(int i, int j)
{   return (i / gcd(i, j)) * j;
}
…
```

```
…
int main(void)
{   int iGcd;
    int iLcm;
    iGcd = gcd(8, 12);
    iLcm = lcm(8, 12);
    printf("%d %d\n", iGcd, iLcm);
    return 0;
}
```

The program is correct

But let's pretend it has a runtime error in **gcd()**…

Using GDB

General GDB strategy:

- Execute the program to the point of interest
  - Use breakpoints and stepping to do that

- Examine the values of variables at that point

Using GDB

Typical steps for using GDB:

(a) Build with –g

```
gcc217 -g testintmath.c -o testintmath
```

- Adds extra information to executable file that GDB uses

(b) Run Emacs, with no arguments

```
emacs
```

(c) Run GDB on executable file from within Emacs

```
<Esc key> x gdb <Enter key> testintmath <Enter key>
```

(d) Set breakpoints, as desired

```
break main
```

- GDB sets a breakpoint at the first executable line of main()

```
break gcd
```

- GDB sets a breakpoint at the first executable line of gcd()

Using GDB

Typical steps for using GDB (cont.):

(e) Run the program

`run`

- GDB stops at the breakpoint in main()
- Emacs opens window showing source code
- Emacs highlights line that is to be executed next

`continue`

- GDB stops at the breakpoint in gcd()
- Emacs highlights line that is to be executed next

(f) Step through the program, as desired

`step` (repeatedly)

- GDB executes the next line (repeatedly)

- Note: When next line is a call of one of your functions:
  - **`step`** command *steps into* the function
  - **`next`** command *steps over* the function, that is, executes the next line without stepping into the function

Using GDB

Typical steps for using GDB (cont.):

(g) Examine variables, as desired

```
print i
print j
print temp
```

- GDB prints the value of each variable

(h) Examine the function call stack, if desired

```
where
```

- GBB prints the function call stack
- Useful for diagnosing crash in large program

(i) Exit gdb

```
quit
```

(j) Exit Emacs

```
<Ctrl-x key> <Ctrl-c key>
```

Using GDB

GDB can do much more:

- Handle command-line arguments

```
run arg1 arg2
```

- Handle redirection of stdin, stdout, stderr

```
run < somefile > someotherfile
```

- Print values of expressions
- Break conditionally
- Etc.