

# COS 217: Introduction to Programming Systems

## Building Multifile Programs with make



**PRINCETON UNIVERSITY**



# But first, this programming alert!

What: Midterm Exam!

When: March 8 10:00am – 10:50am  
(2 weeks from this Wednesday)

Where:

P01, P02, P03, P05, P06, P07: Friend 101 (Here!)

P04, P04A: CS 105

How: On paper. Closed book, but 1 one-sided study sheet allowed.

Why: It's fun right?

Info: <https://www.cs.princeton.edu/courses/archive/spr23/cos217/exam1.html>



# Agenda



## **Motivation for Make**

Make Fundamentals

Non-File Targets

Macros



# Multi-File Programs

intmath.h (interface)    intmath.c (implementation)    testintmath.c (client)

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

```
#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;
}
```

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

int main(void)
{
    int i, 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;
}
```

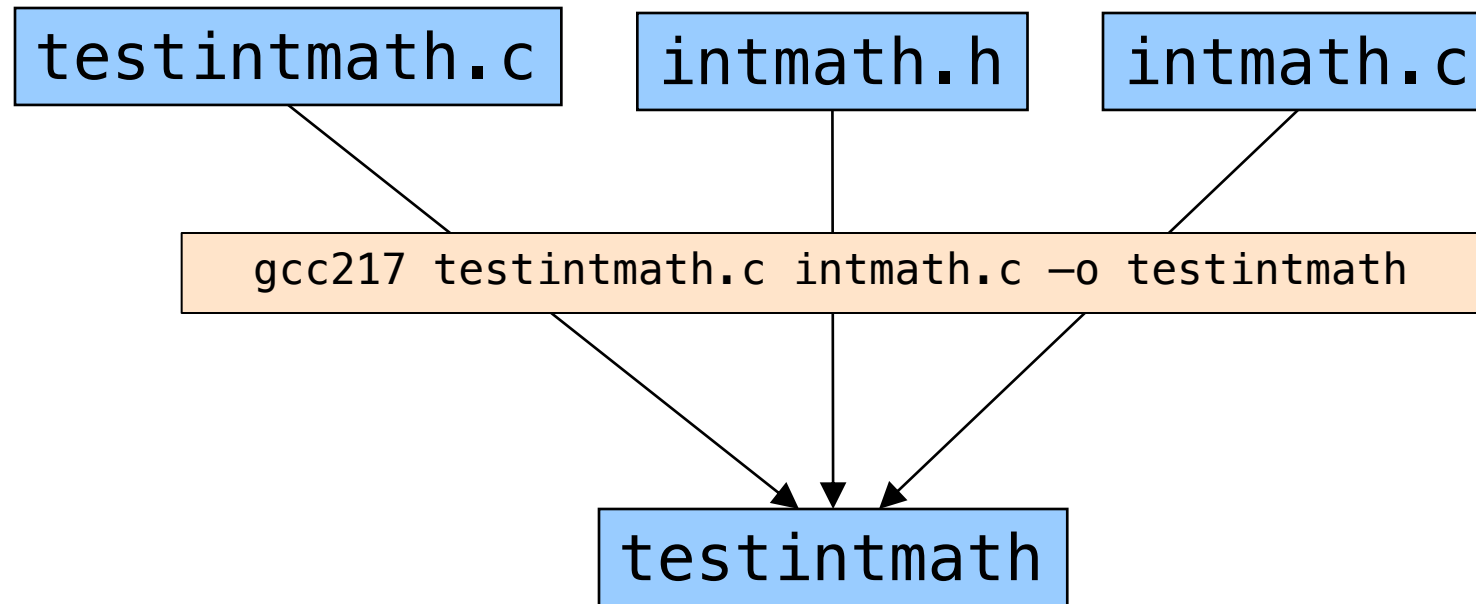
Note: intmath.h is  
#included into intmath.c  
and testintmath.c



# Motivation for Make (Part 1)

## Building testintmath, approach 1:

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



<https://xkcd.com/303/>



THE #1 PROGRAMMER EXCUSE  
FOR LEGITIMATELY SLACKING OFF:  
"MY CODE'S COMPILING."

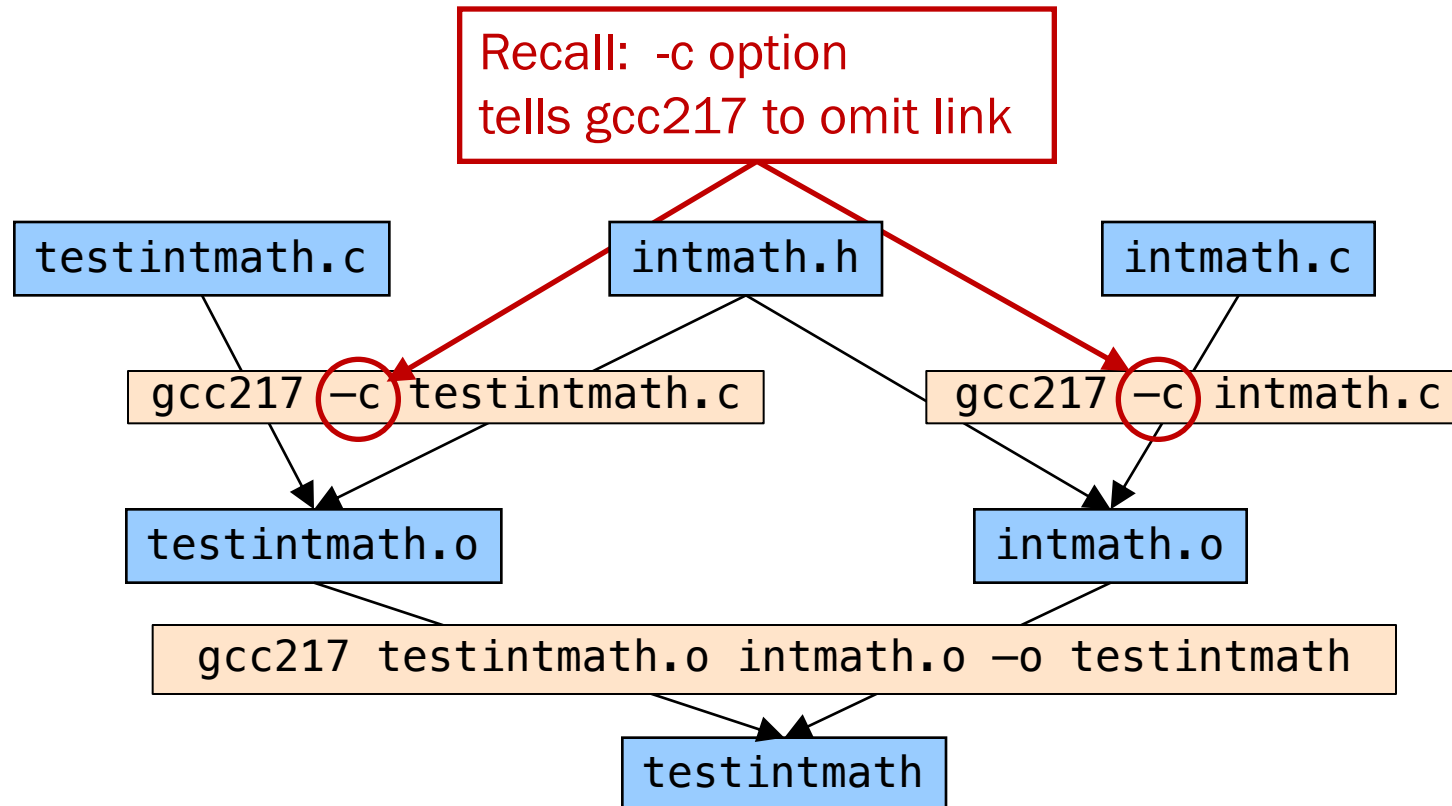




# Motivation for Make (Part 2)

## Building `testintmath`, approach 2:

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



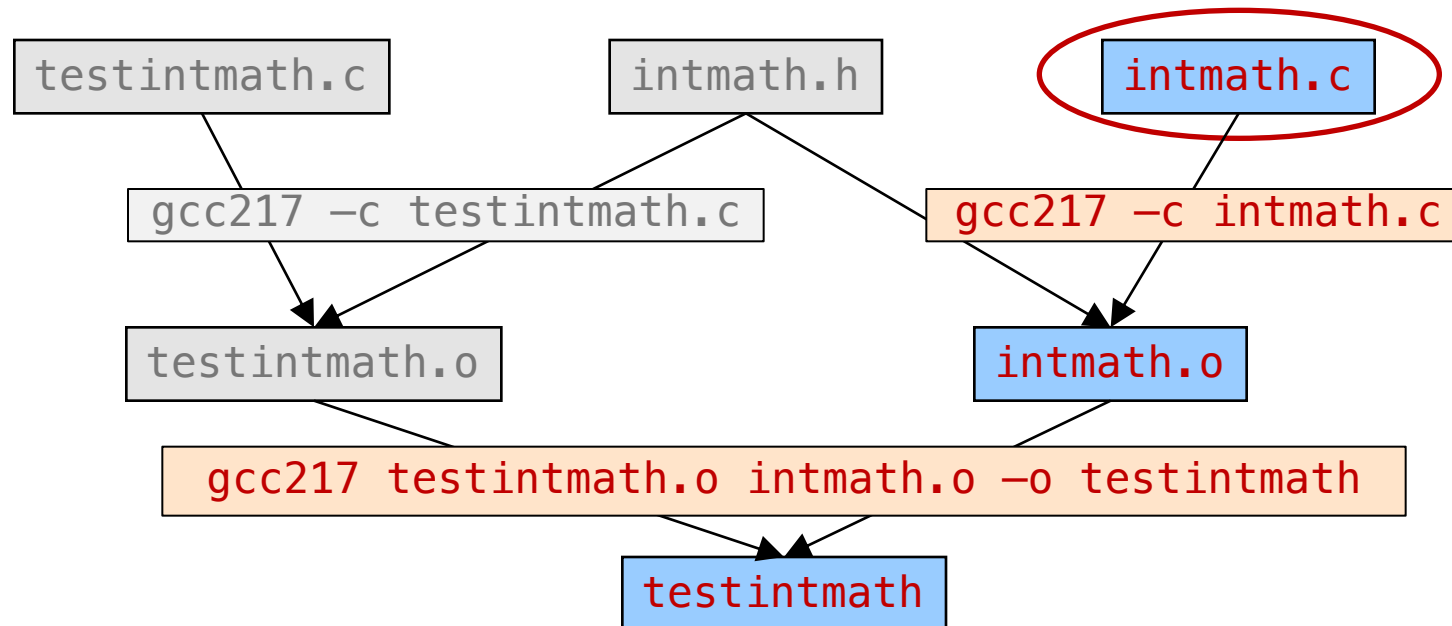


# Partial Builds

## Approach 2 allows for **partial builds**

- Example: Change `intmath.c`
  - Must rebuild `intmath.o` and `testintmath`
  - No need to rebuild `testintmath.o`

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



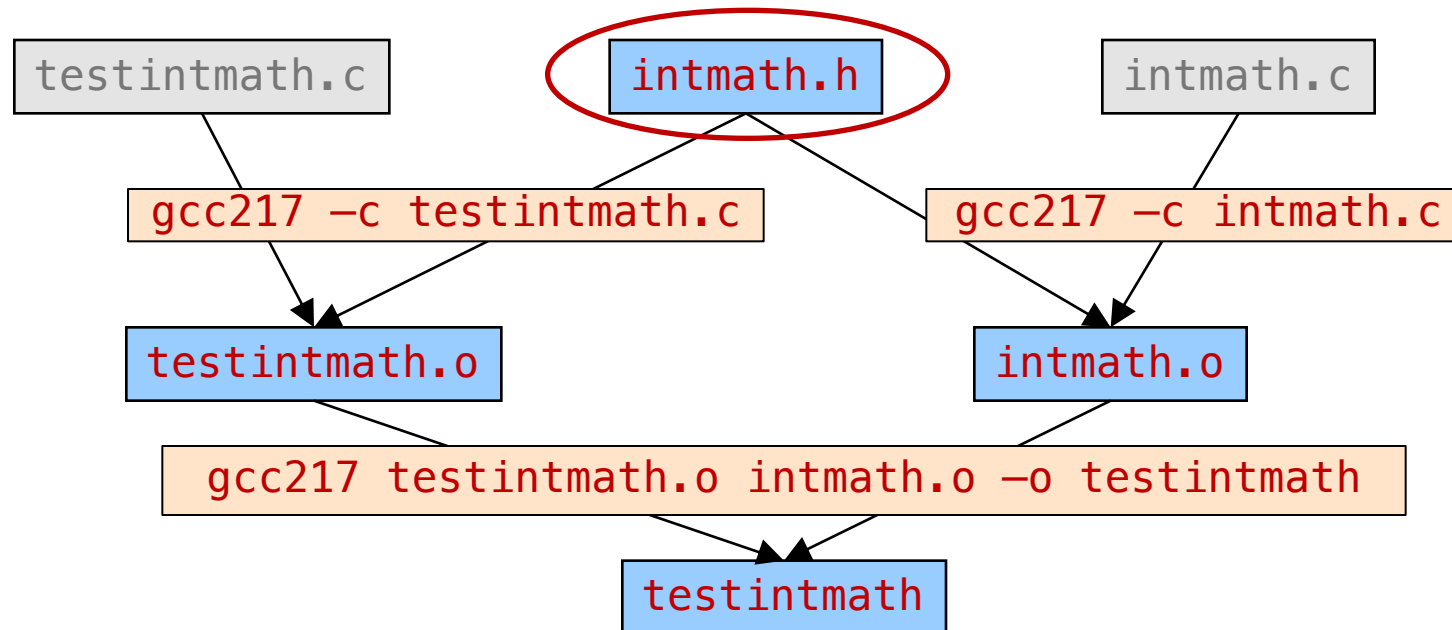




# Partial Builds

However, changing a .h file can be more dramatic

- Example: Change `intmath.h`
  - `intmath.h` is `#include`'d 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!

# Obligatory Princeton Context



## Stuart Feldman '68

- Chief Scientist at Schmidt Futures
- Former President of ACM
- AAAS, IEEE, and ACM fellow
- Board Chair of



Created make at  
Bell Labs in 1976

# Agenda



Motivation for Make

**Make Fundamentals**

Non-File Targets

Macros



# 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 executable binary file
- Default is first one defined in **makefile**



# Dependency Rules in Makefile

## Dependency rule syntax

```
target: dependencies  
    <tab>command
```

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

## Dependency rule semantics

- Build **target** if it doesn't exist
- Rebuild **target** iff it is older than at least one of its **dependencies**
- Use **command** to do the build
- Work recursively; examples illustrate...



# Make gotcha: tab means tab not *k* spaces

`<tab>`command

The first character of the line with the command must be an *actual tab character*, ASCII character 9. Cryptic error for failing to do so:  
`*** missing separator. Stop.`

Feldman explains the genesis:

"Within a few weeks of writing Make, I already had a **dozen** friends who were using it" ... "I didn't want to upset them" ... "So instead I wrought havoc on tens of millions."

--Cobbled from Brian Kernighan's *UNIX: A History and a Memoir* and [Michael Stillwell](#)



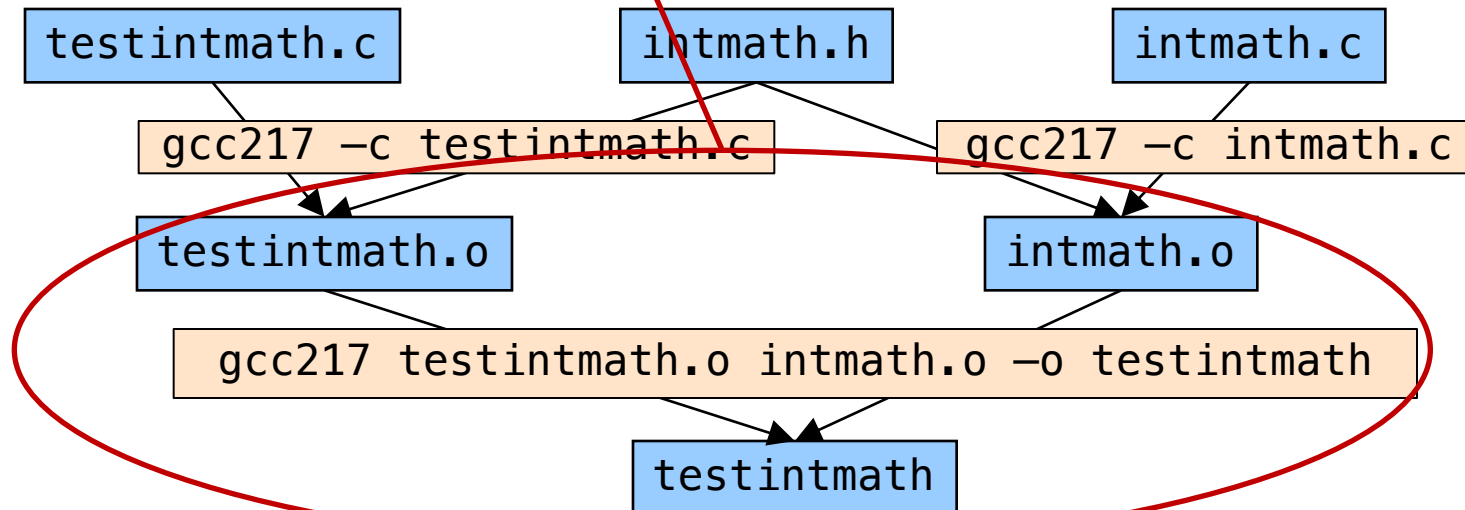
# Makefile Version 1

## 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
```







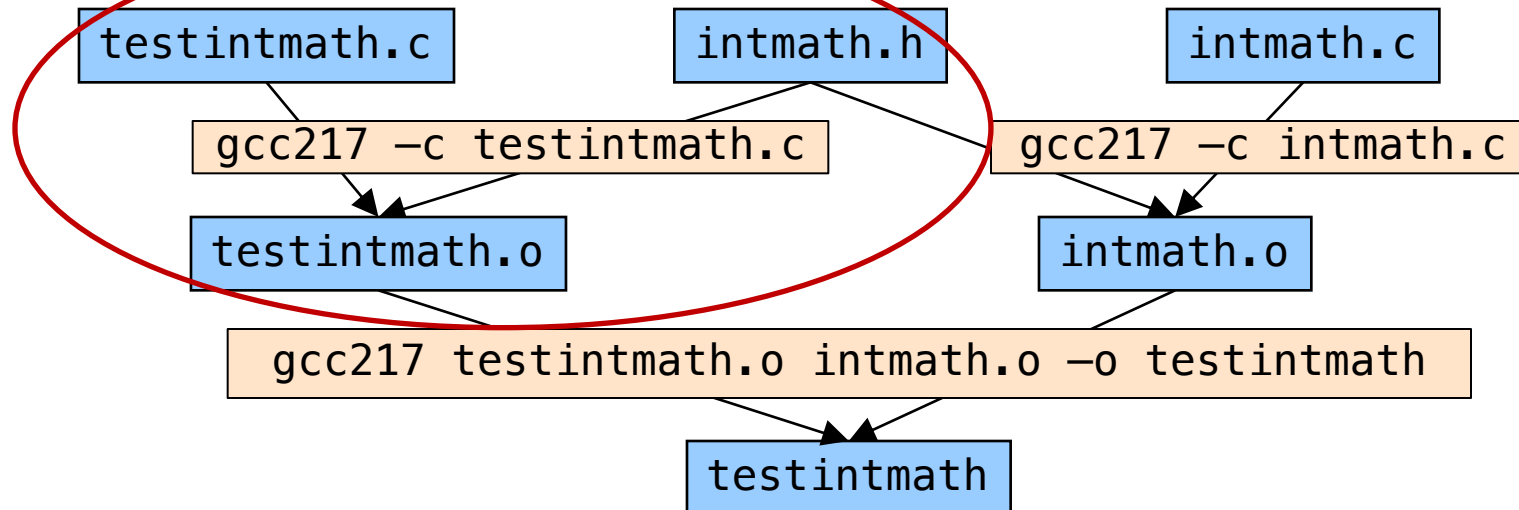
# Makefile Version 1

## Makefile

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

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

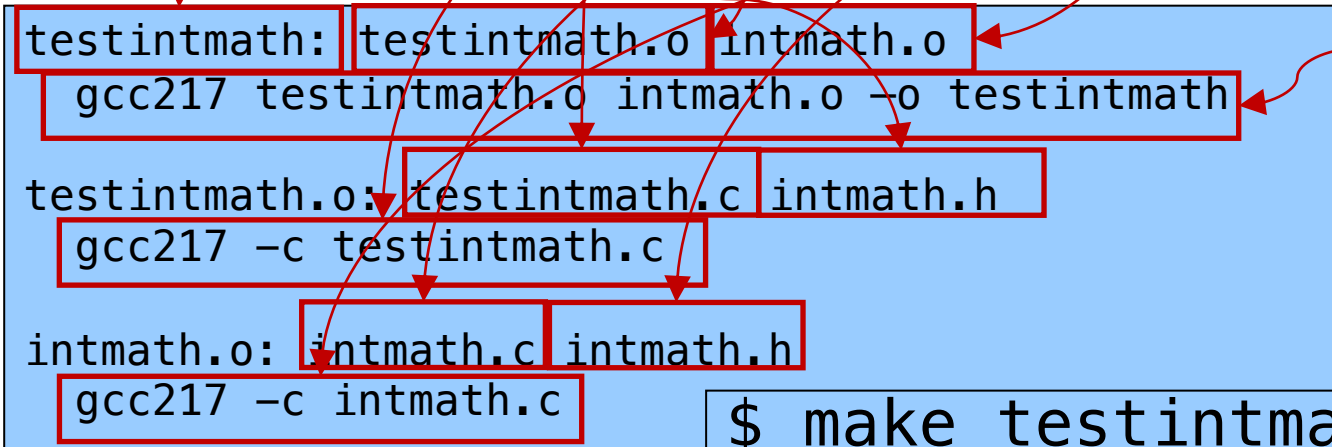
intmath.o: intmath.c intmath.h
gcc217 -c intmath.c
```





# Version 1 in Action

Does <b>testintmath</b> exist?	No! Does testintmath.o exist?	And does intmath.o exist?
	No! Recur! Does testintmath.c?	No! Recur! Does intmath.c?
	Yes! Does intmath.h exist?	Yes! Does intmath.h exist?
	Yes! Produce testintmath.o!	Yes! Produce intmath.o!



Now finally produce **testintmath**!

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



# 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

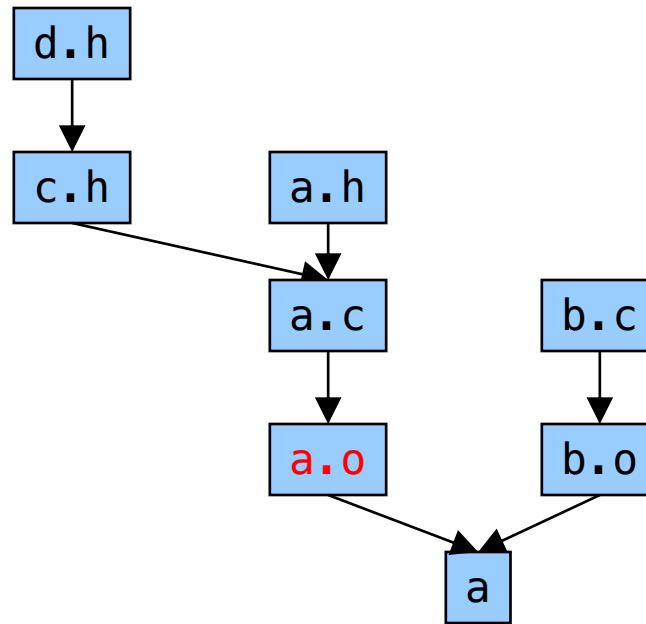


# make up your mind



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

- A. `a`
- B. `a.c`
- C. `a.c b.c`
- D. `a.h c.h d.h`
- E. `a.c a.h c.h d.h`

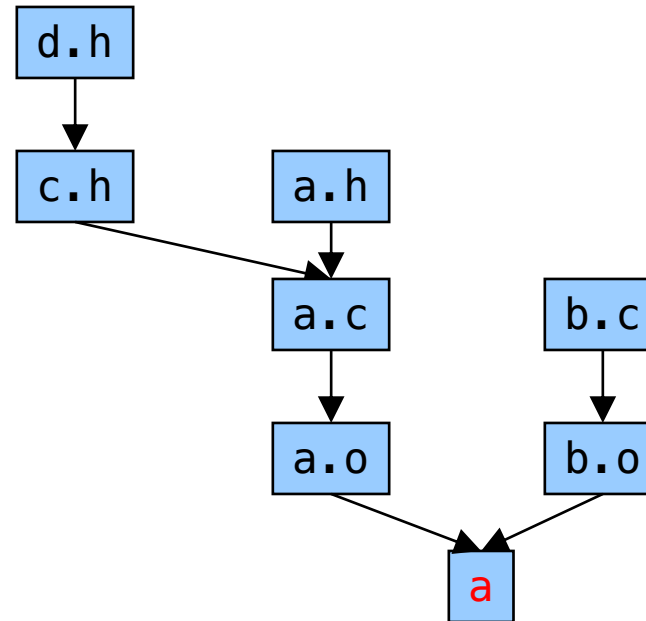




# building understanding



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 (aka “pseudotargets”)

Take advantage that make doesn't check that a target actually gets built to add useful shortcuts!

Commonly defined non-file targets:

- **make all**: create the final executable binary file(s), often the first target listed in the Makefile
- **make clean**: delete all .o files, executable binary file(s)
- **make clobber**: delete all Emacs backup files, all .o files, executable(s)

```
all: testintmath
clobber: clean
    rm -f *~ \#\*\#
clean:
    rm -f testintmath *.o
```

Commands in the example

- `rm -f`: remove files without querying the user
- Files ending in ‘~’ and starting/ending in ‘#’ are Emacs backup and autosave files



# 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
```

```
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
```



# More Makefile Gotchas

## Beware:

- Bears repeating: each command (second line of each dependency rule) must begin with a tab character, not spaces – configure your editor accordingly!
- Use the `rm -f` command with caution  
(More generally, be careful about automatically doing anything you can't undo!)
- Have something sensible as your default command  
(Users are likely to just type `make`, out of habit or ignorance.)





# Making Makefiles

## In this course

- Create Makefiles manually
- Perhaps start from Makefiles from this lecture?

## Beyond this course

- Can use tools to generate Makefiles
  - See `mkmf`, others
- Copy-paste-edit forever!



# 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
  - `$(CC)` : the first dependency of the rule
  - `$(?)` : 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.  
We'll never ask you to write these.



# 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 almost certainly confusing).  
We'll ask you never to write these! (*cf.* previous)





# Makefile Version 4

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

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

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

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

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

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

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

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

```
# Macros  
CC = gcc217  
CFLAGS =  
  
# 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
```

Progressively terser but  
more confusing. Just don't.



# Implicit Rule Gotcha

## 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
```





# Make Resources

GNU make <http://www.gnu.org/software/make/manual/make.html>

*C Programming: A Modern Approach*  
(King) Section 15.4

