Building Multi-File Programs with the `make` Tool

Agenda

Motivation for Make

Make Fundamentals

Non-File Targets

Macros

Implicit Rules

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)

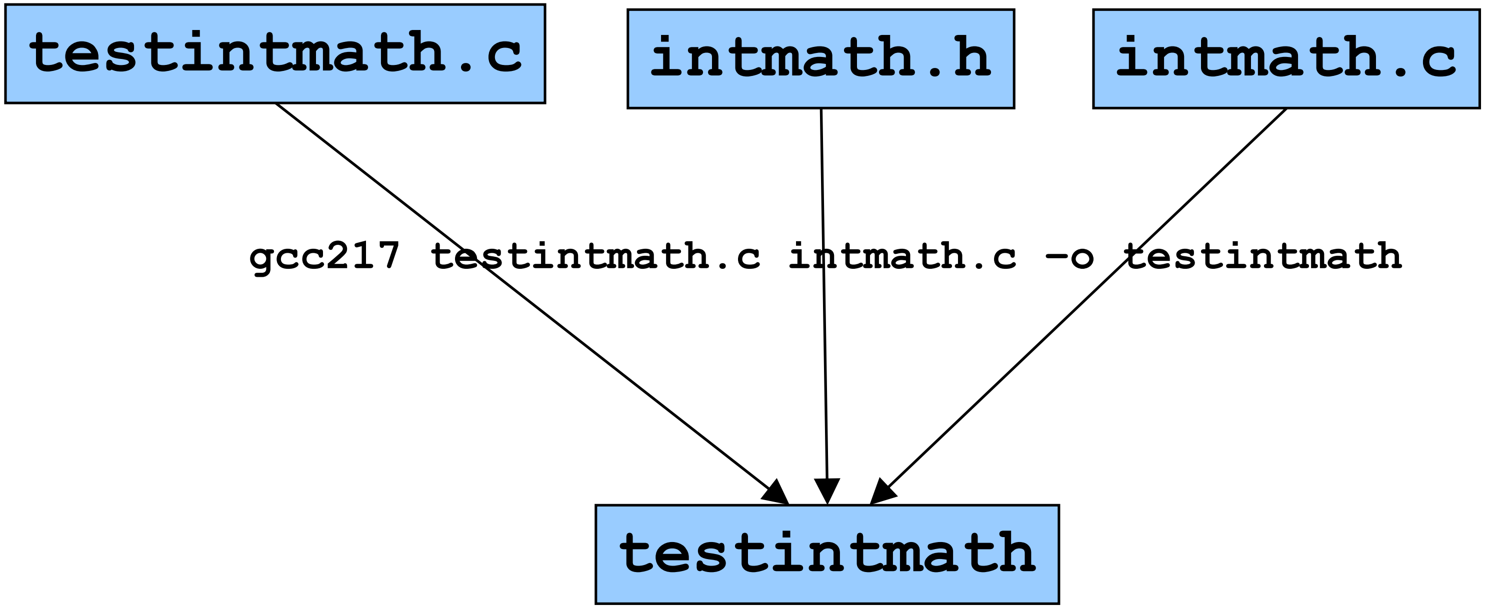
```
#include "intmath.h"
#include <stdio.h>

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

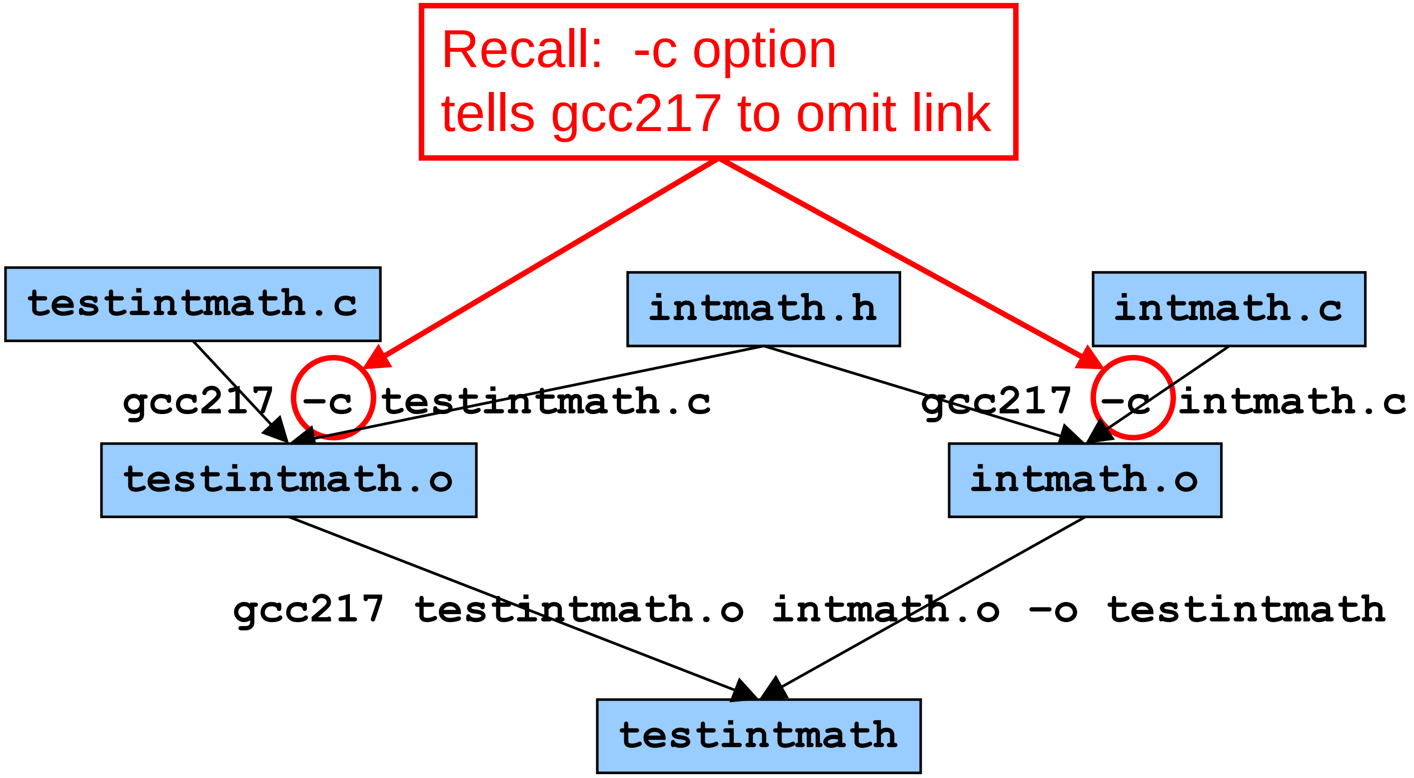


```
gcc217 testintmath.c intmath.c -o testintmath
```

Motivation for Make (Part 2)

Building **`testintmath`**, approach 2:

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

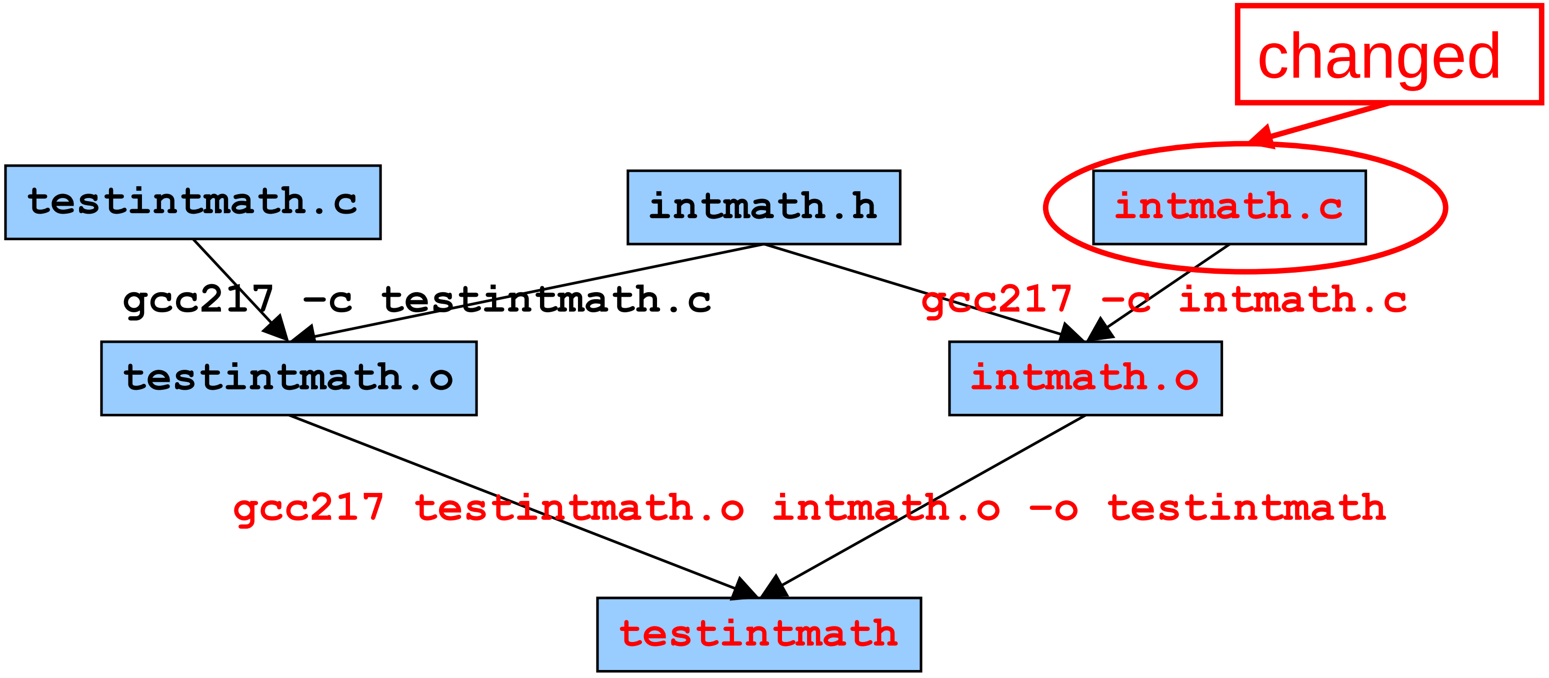


Recall: -c option
tells gcc217 to omit link

Partial Builds

Approach 2 allows for **partial builds**

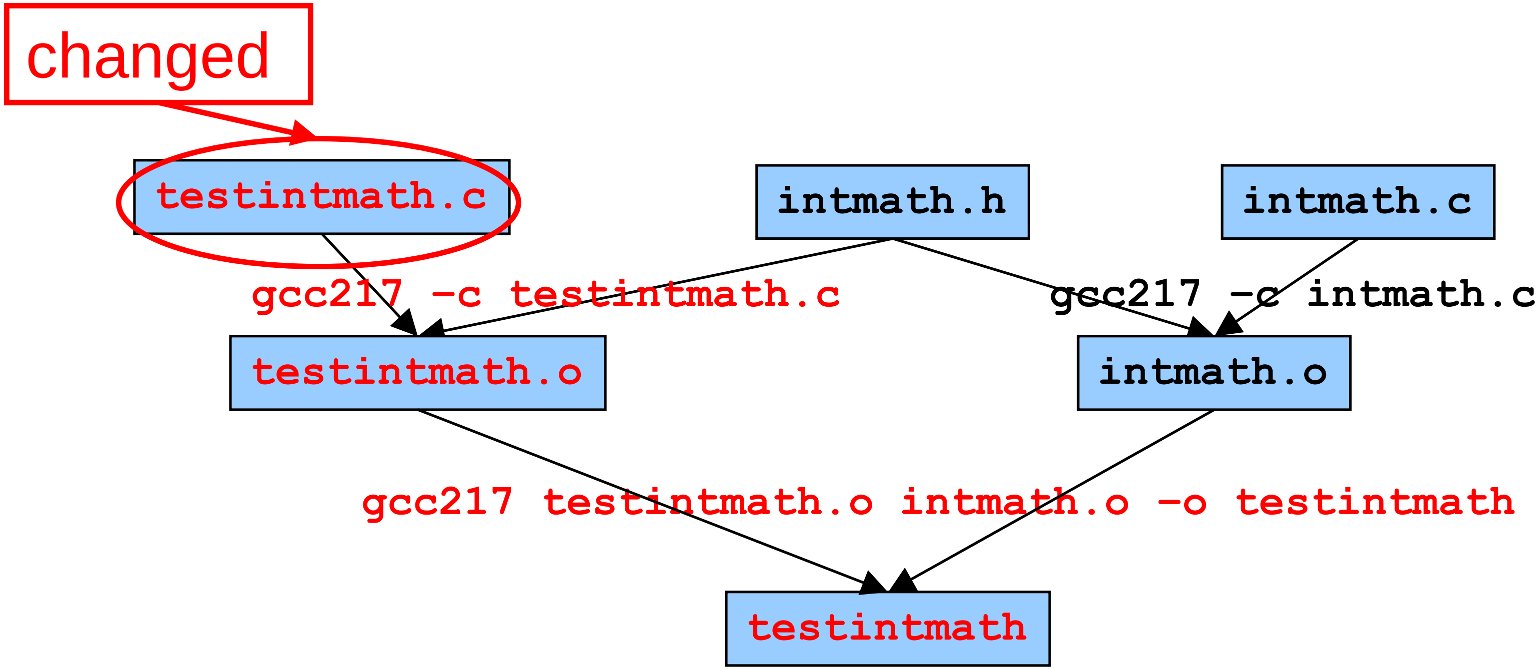
- Example: Change **`intmath.c`**
  - Must rebuild **`intmath.o`** and **`testintmath`**
  - Need not rebuild **`testintmath.o`**!!!



Partial Builds

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

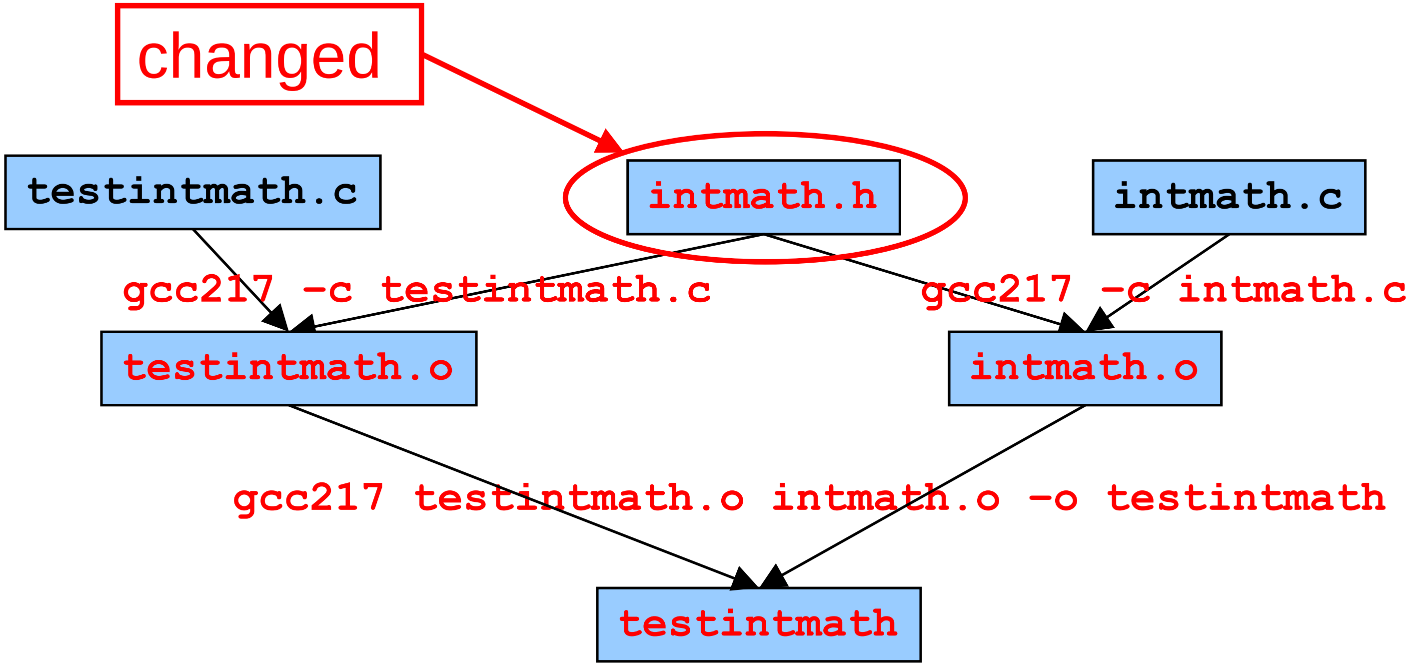
If program contains many .c files, could save many hours of build time



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`**
    - Changing **`intmath.h`** effectively changes **`testintmath.c`** and **`intmath.c`**
  - Must rebuild **`testintmath.o`**, **`intmath.o`**, and **`testintmath`**



Wouldn’t It Be Nice…

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`**!

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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: dependencies
    <tab>command
```

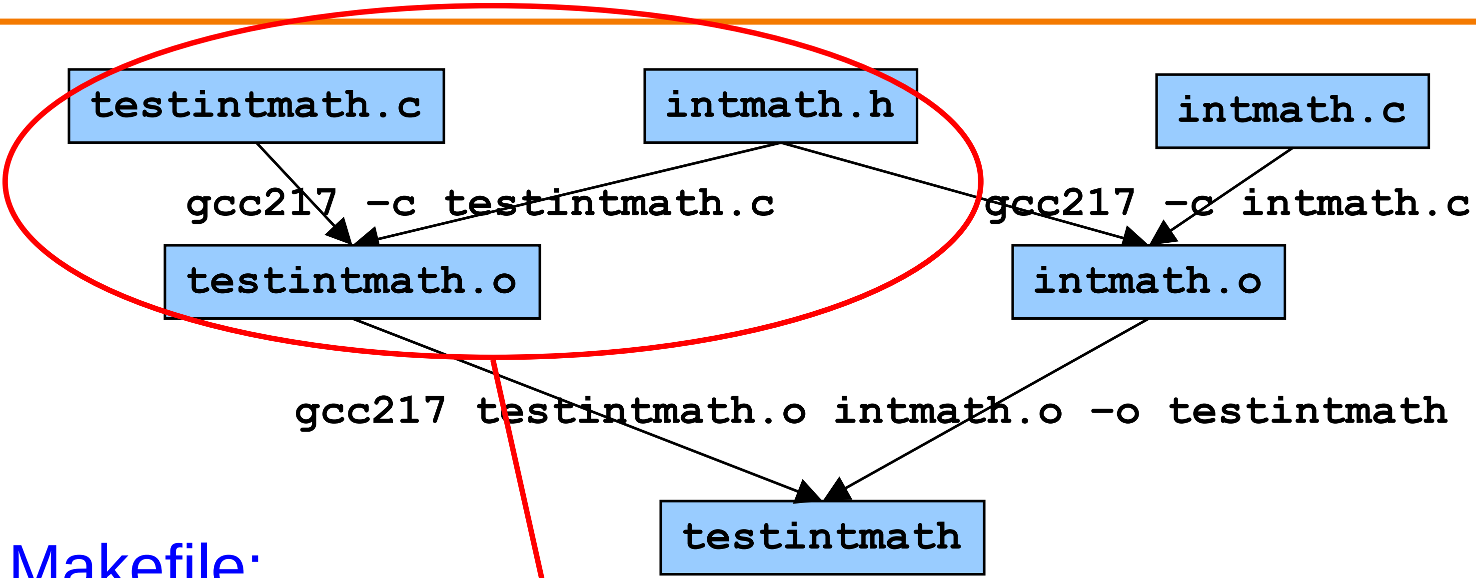
- `target`: the file you want to build
- `dependencies`: the files on which the target depends
- `command`: (after a TAB character) what to execute to create the target

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



testintmath.c

intmath.h

intmath.c

`gcc217 -c testintmath.c`

`gcc217 -c intmath.c`

testintmath.o

intmath.o

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

testintmath

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

Agenda

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Non-File Targets

Adding useful shortcuts for the programmer

- `make all`: create the final executable binary file
- `make clean`: delete all .o files, executable binary file
- `make clobber`: delete all Emacs backup files, all .o files, executable

Commands in the example

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

Implicit Rules

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 build commands

```
CC = gcc217
```

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

Agenda

Motivation for Make

Make Fundamentals

Non-File Targets

Macros

Implicit Rules

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
```

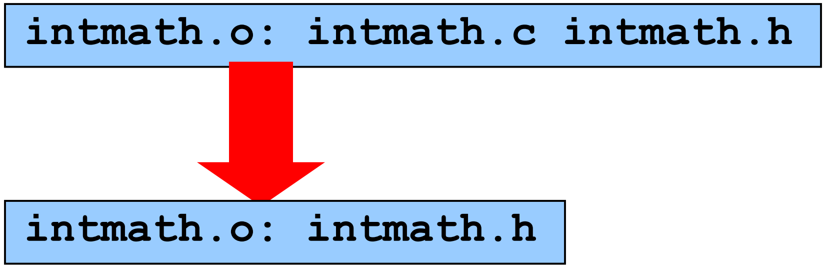
Version 4 in Action

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

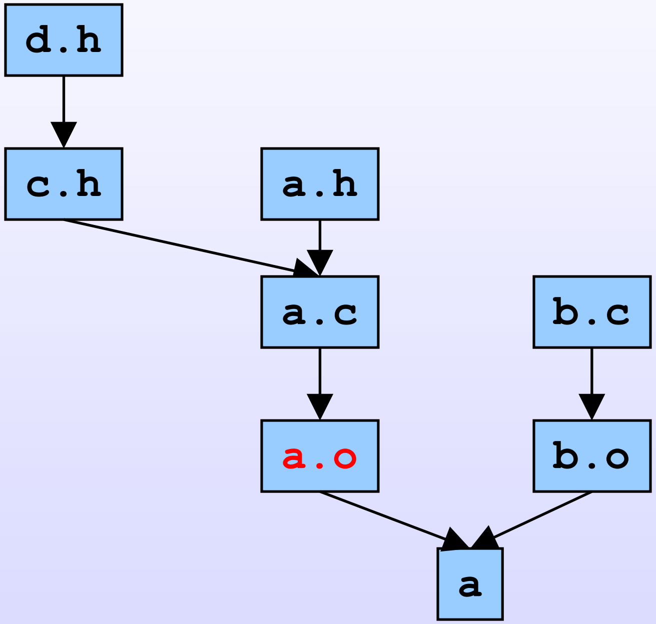
```
# Macros
CC = gcc217
# CC = gcc217m
CFLAGS =
# CFLAGS = -g
# CFLAGS = -D NDEBUG
# CFLAGS = -D NDEBUG -O

# 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

iClicker Question

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



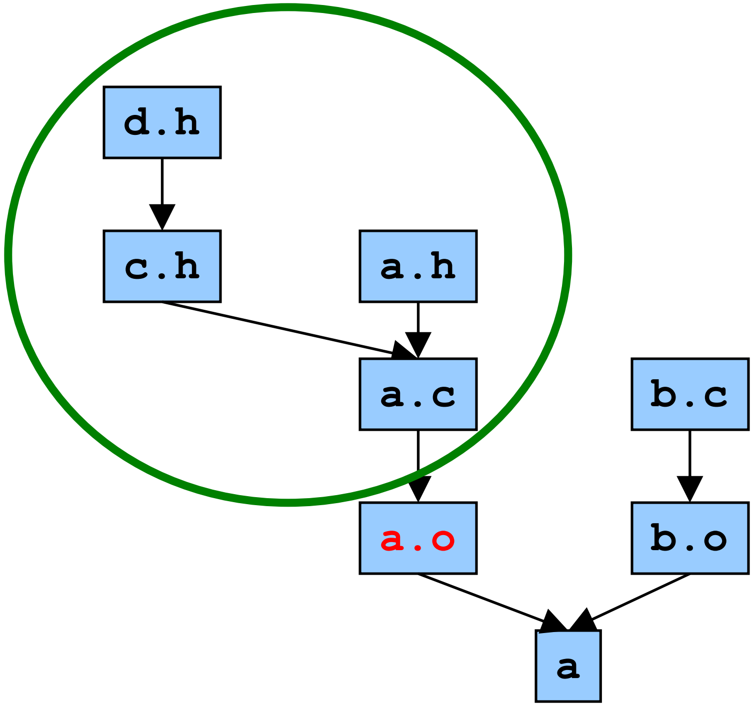
A. **`a.c`**

B. **`a.c a.h`**

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

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

Makefile Guidelines



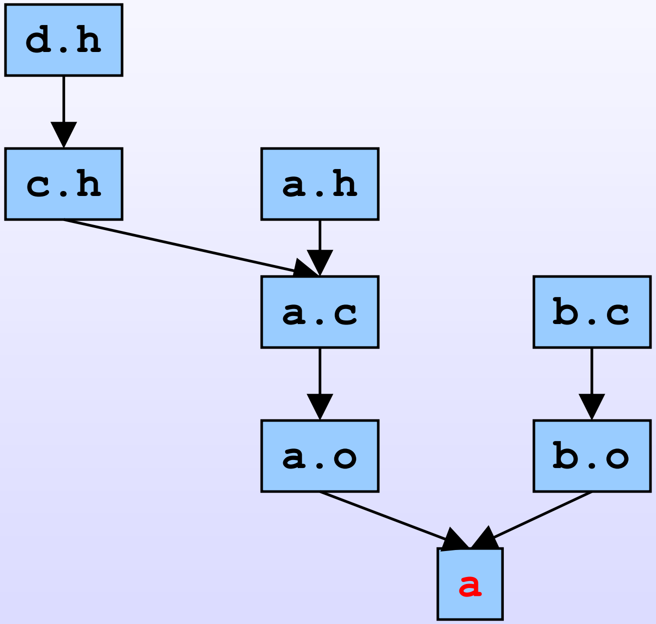
`a.o: a.h c.h d.h`

In a proper Makefile, each object file:

- Depends upon its .c file (but can rely on an implicit dependency)
  - Does not depend upon any other .c file
  - Does not depend upon any .o file
- Depends upon any .h files that are #included **directly or indirectly**

iClicker Question

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



A. `a.o b.o`

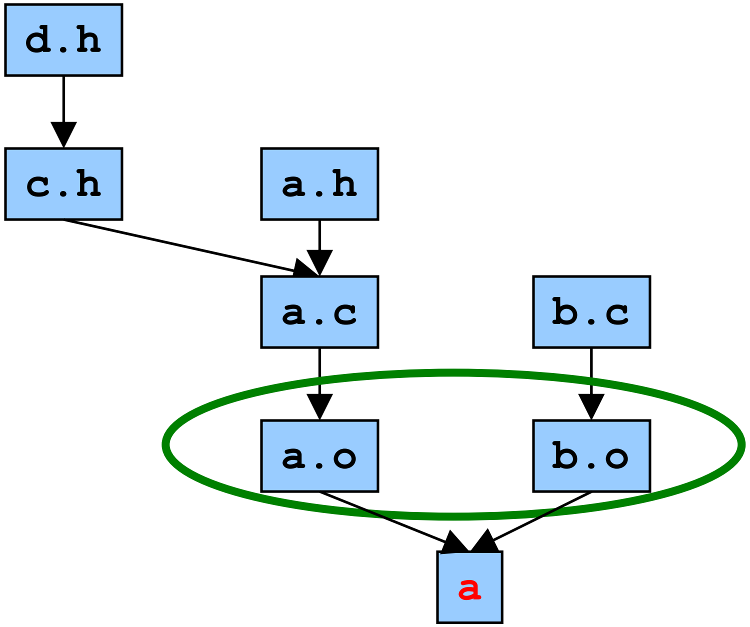
B. `a.o b.o a.c b.c`

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`

Makefile Guidelines



`a: a.o b.o`

In a proper Makefile, each executable:

- Depends upon the .o files that comprise it
- Does not depend upon any .c files
- Does not depend upon any .h files

Making Makefiles

In this course

- Create Makefiles manually

Beyond this course

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

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
- 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

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)

Implicit rules (Makefile versions 4 and 5)

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
hello.c:7: warning: ISO C forbids an empty
translation unit
```

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: error: expected ';' before 'return'
```

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: warning: implicit declaration of function
'prinf'
/tmp/ccLSPMTR.o: In function `main':
hello.c:(.text+0x1a): undefined reference to `prinf'
collect2: ld returned 1 exit status
```

Understand Error Messages

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

What does this error message even mean?

```
$ gcc217 hello.c -o hello
hello.c:7: error: two or more data types in declaration specifiers
hello.c:7: warning: return type of 'main' is not 'int'
```

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 semicolons
  - At ends of structure type definitions
  - At ends of function declarations
- Work incrementally
  - Start at first error message
  - Fix, rebuild, repeat

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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

(1) Understand error messages

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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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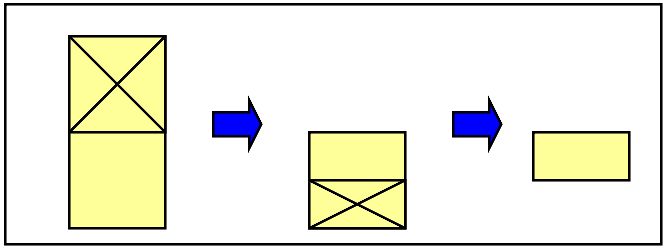
Divide and Conquer

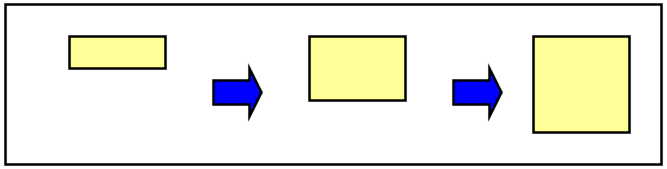
Divide and conquer: To debug a **program**…

- 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 code 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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(6) Display output

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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

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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

(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

(8) Focus on recent changes

Use a Debugger

Use a debugger

- Alternative to displaying output

The GDB Debugger

GNU **Deb**ugger

- 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 1

Agenda

(1) Understand error messages

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(8) Focus on recent changes

Focus on Recent Changes

Focus on recent changes

- Corollary: Debug now, not later

Difficult:

(1) Compose entire program
(2) Test entire program
(3) Debug entire program

Easier:

(1) Compose a little
(2) Test a little
(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:

(1) Change code
(2) Note new bug
(3) Try to remember what changed since last version

Easier:

(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: 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()**…

Appendix 1: 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

Appendix 1: 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()

Appendix 1: 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

Appendix 1: 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>
```

Appendix 1: 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.