Large Programs: Linking and `make`

C Programming and Software Tools

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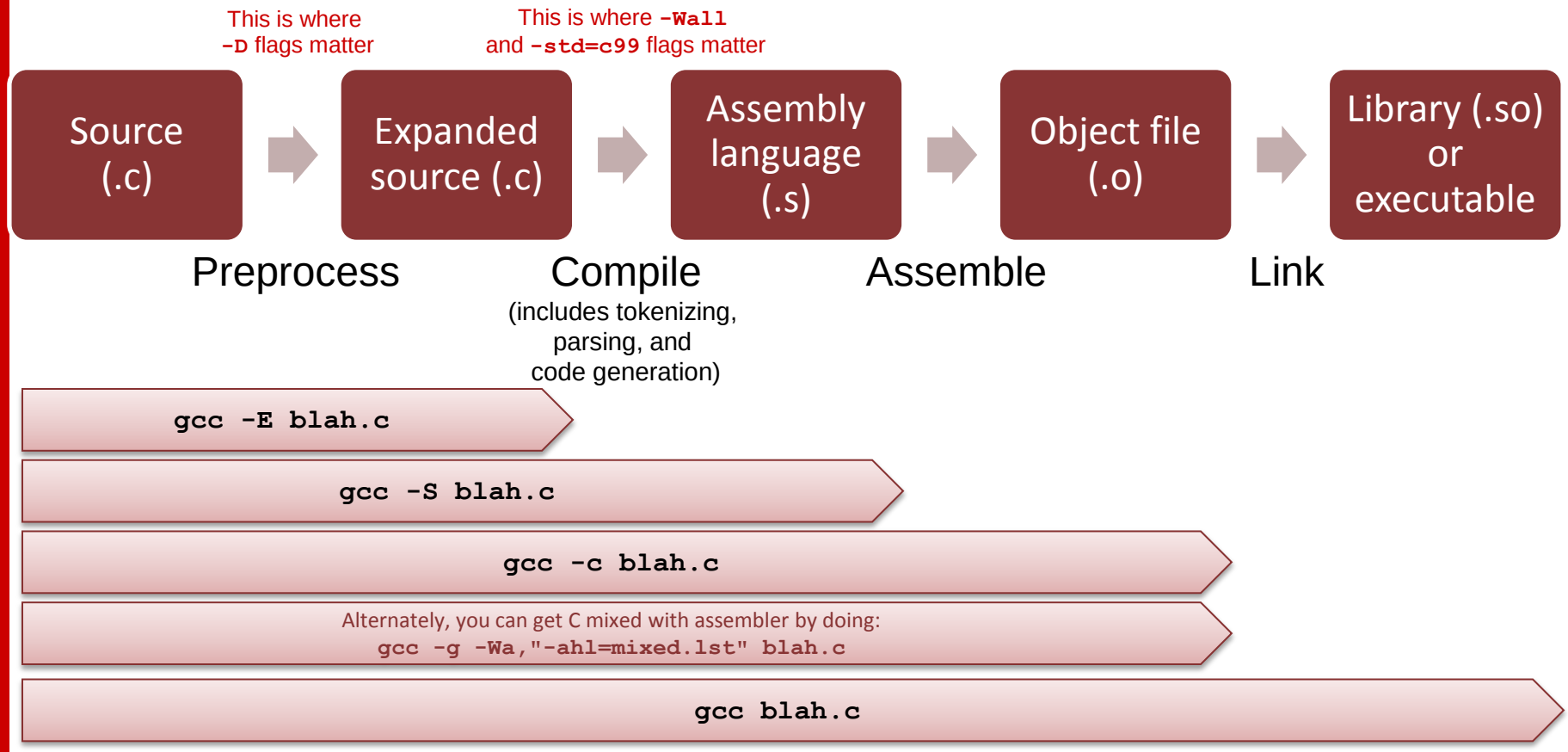
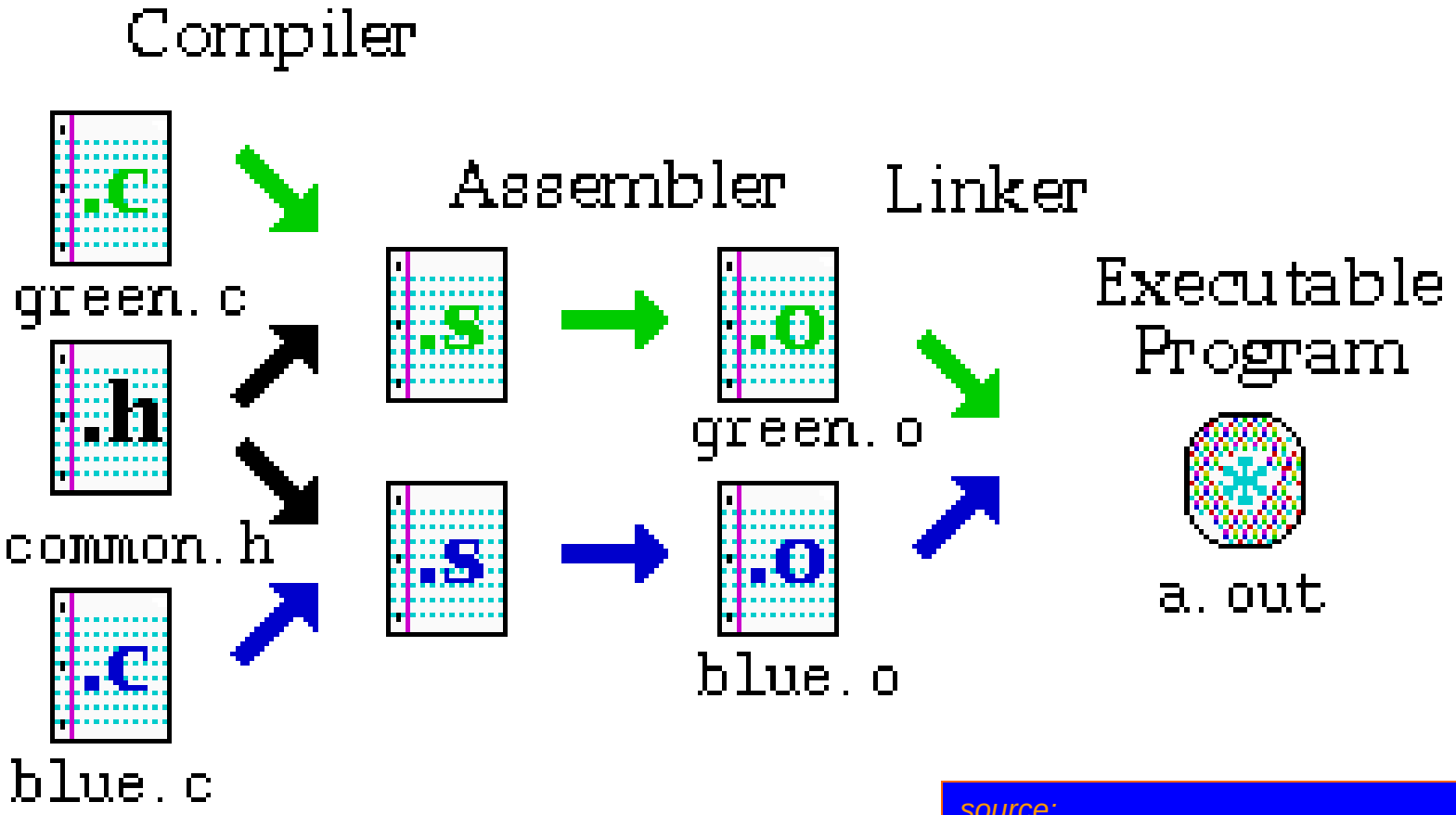
Separate Compilation

- In Java, every class is a separate source code file
- In C, the programmer determines how to split a program up into source code files (*modules*)
  - rules/conventions for doing this?
- Each module is compiled independently to produce an object (.o) file
  - object files are then linked together to produce an executable application
  - all managed by gcc
- Benefits of separate modules?

Steps in compiling C



Steps in Compiling



source:
http://www.eng.hawaii.edu/Tutor/Make/1-2.html

```
> gcc -Wall -std=c99 green.c blue.c
```

What Does a Linker Do?

- Integrates (unifies) the address space of the separately-compiled modules
  - creates a single symbol table
  - resolves *external references* between modules
- Compile separately, then link together

generate object code, without linking

```
> gcc -Wall -std=c99 -c green.c
```

```
> gcc -Wall -std=c99 -c blue.c
```

link object code files together, produce executable

```
> gcc green.o blue.o -o a.out
```

Linking... (cont'd)

- Two types of linkers
  - static linking (at compile time)
  - dynamic linking (at run time)
- Dynamic: At runtime, link to a function the first time it is called by the program
- Ex.: common OS functions (API)
  - placed into DLL or shared library
  - loaded into memory at system boot time
- Benefits (vs. static linking) ?

Here are some technically possible but never actually used methods of writing multi-file programs.

- The goal is to show you WHY you do it the right way, which will be shown later.

External Variables in C

- Global variables and functions can be referenced by (are in the scope of) other modules
- To link to a variable or function declared in another file, use the keyword **`extern`**
- **`extern`** declares the variable/function, but doesn't define it

File p.c

```
#include <stdio.h>
extern int f( int );
int x = 3;
int main() {
    x++;
    printf("%d %d\n",
           x, f(x));
    return 0;
}
```

File q.c

```
extern int g ( int );
int f ( int a ) {
    int x = 5;
    return g(x * a);
}
```

File r.c

```
int g ( int b ) {
    return b * 3;
}
```

```
> gcc p.c q.c r.c –o pgm
```

External... (cont'd)

Extern declarations commonly collected in `.h` files, which are `#include`'d at start of `.c` file

- Warning: make sure names in files don't conflict

`static` keyword before global variable x:

- visible only within this module
- information hiding!

File `p.c`

```
#include <stdio.h>
extern int f( int );
static int x = 3;
int main() {
    x++;
    printf("%d %d\n",
            x, f(x));
    return 0;
}
```

File `q.c`

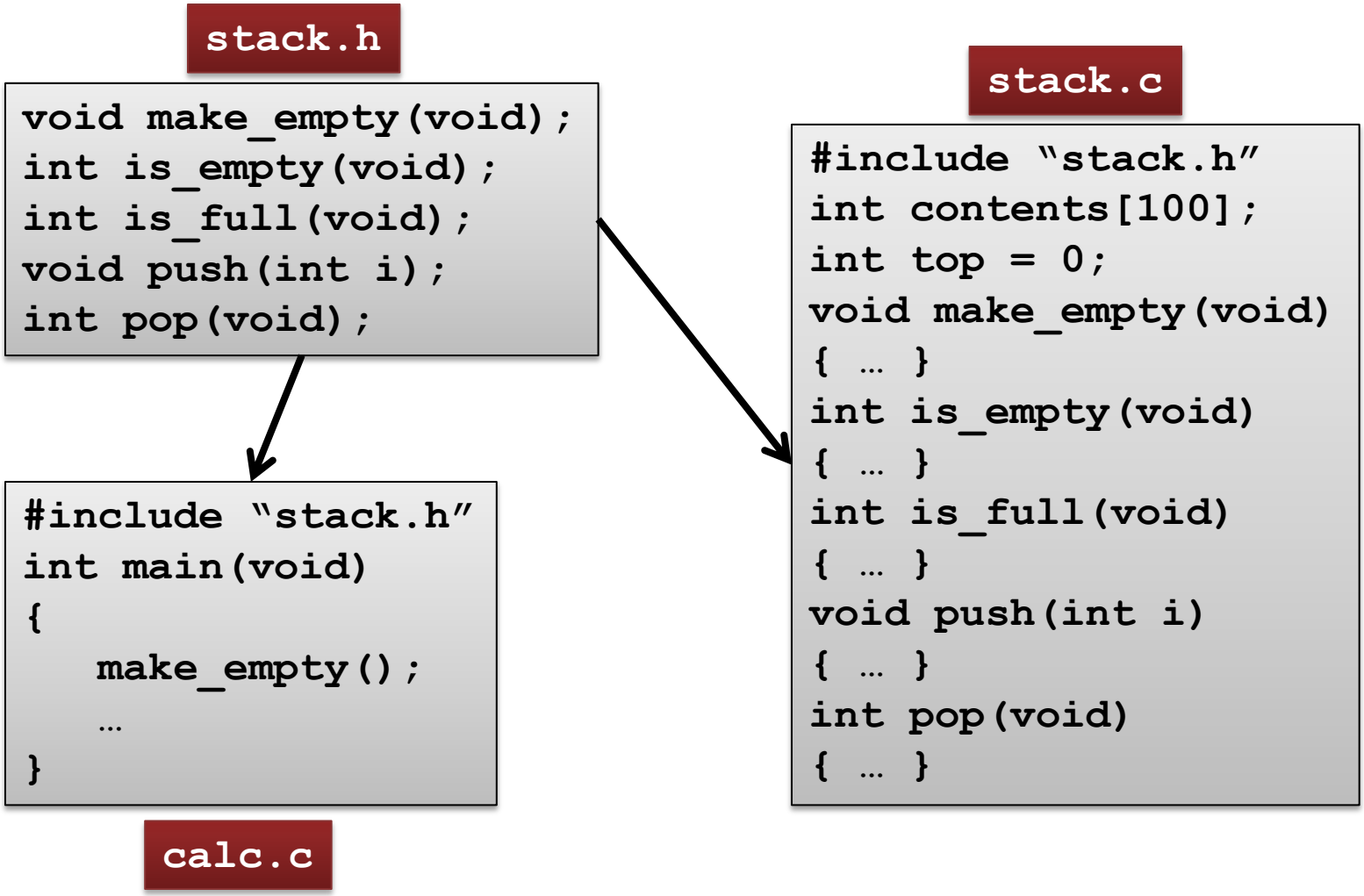
```
extern int g ( int );
int x = 5;
int f ( int a ) {
    return g(x * a);
}
```

No conflicts – `x` in `p.c` different than `x` in `q.c`, even though both are global variables

Header Files

- **`extern`** allows for function and variable prototypes that are shared between C files.
  - What happens if a function **`f`** declared in **`foo.c`** is called in 50 other files?
- Instead, we can include **`f`**'s prototype in a header file and all files that use **`f`** can include the header.
  - The file that defines **`f`** should also include the header file
- Files are named **`*.h`**, where **`*`** typically matches the name of the **`*.c`** file that contains the function definitions

Simple Header File Example



Okay, here are the real best practices for multi-file programs

Header file rules (1)

- Any C file with content you want to use elsewhere has a **corresponding H file**
- **Functions:**
  - **"Public" (available in other C files)?** Put its prototype in the H file
  - **"Private" (this C file only)?** Declare it "**`static`**" in your C file
- **Global variables:**
  - **"Public" (available in other C files)?**
    - Declare it in your C file
    - Declare it with the "**`extern`**" keyword in your H file
    - *Try to avoid needing public variables, though.*
  - **"Private" (this C file only)?** Declare it "**`static`**" in your C file.
- **Structs/typedefs/unions:**
  - **"Public" (available in other C files)?** Put it in the H file.
  - **"Private" (this C file only)?** Put it in the C file.

Header file rules (2)

- Surround your H file with "**multiple inclusion protection**" :
  - my_file.h:

```
#ifndef MY_FILE_H
#define MY_FILE_H

// prototypes and stuff here

#endif // MY_FILE_H
```

- A C file always includes its own H file, so blah.c has:
  `#include "blah.h"`
- Want to **use code/vars** from blah.c elsewhere?
  `#include "blah.h"`
- When you're done, be sure to **link** the O files from all these C files together when you make your binary.

```
gcc -c -o this.o this.c
gcc -c -o that.o that.c
gcc -o myapp this.o that.o
```

Review the example program

- See nbody.c and associated files…

Linking to an External Library

Program **prog.c**:

```
extern int sub1(void), sub2(void);
int main(void) {
    …
    x = sub1();
    y = sub2();
```

defined in a library of functions

Using the library

```
> gcc pgm.c -L$HOME/lib -lsubs -o pgm
```

directory that contains the library

the name of the library

The order of the options can be important (check compiler)!

- **-l<libname>** may be required to come after the source code files are listed

Creating Libraries (1)

- 1: Compiling with Position Independent Code

```
$ gcc -c -Wall -Werror -fpic foo.c
```

- 2: Creating a shared library from object file(s)

```
$ gcc -shared -o libfoo.so foo.o
```

- 3: Linking with a shared library
  - Let's compile our main.c and link it with libfoo.
  - The -lfoo option is not looking for foo.o, but libfoo.so – GCC assumes that all libraries start with 'lib' and end with .so or .a (.so is for shared object or shared libraries, and .a is for archive, or statically linked libraries).

```
$ gcc -Wall -o test main.c -lfoo
/usr/bin/ld: cannot find -lfoo
collect2: ld returned 1 exit status
```

  - We need to tell GCC where to find the shared library (current directory doesn't count). We do this with -L:

```
$ gcc -L/home/username/foo -Wall -o test main.c -lfoo
```

From: http://www.cprogramming.com/tutorial/shared-libraries-linux-gcc.html

Creating Libraries (2)

- 4: Making the library available at runtime
  - Try to run it:

```
$ ./test
./test: error while loading shared libraries: libfoo.so:
cannot open shared object file: No such file or directory
```

  - Have to update LD_LIBRARY_PATH environment variable (or for permanent change, use `ldconfig` (advanced)):

```
$ setenv LD_LIBRARY_PATH /home/username/foo:$LD_LIBRARY_PATH
$ ./test
This is a shared library test...
Hello, I'm a shared library
```

- NOTE: This stuff is Linux/UNIX specific. On Windows (except for Cygwin), you use DLLs and everything's totally different.

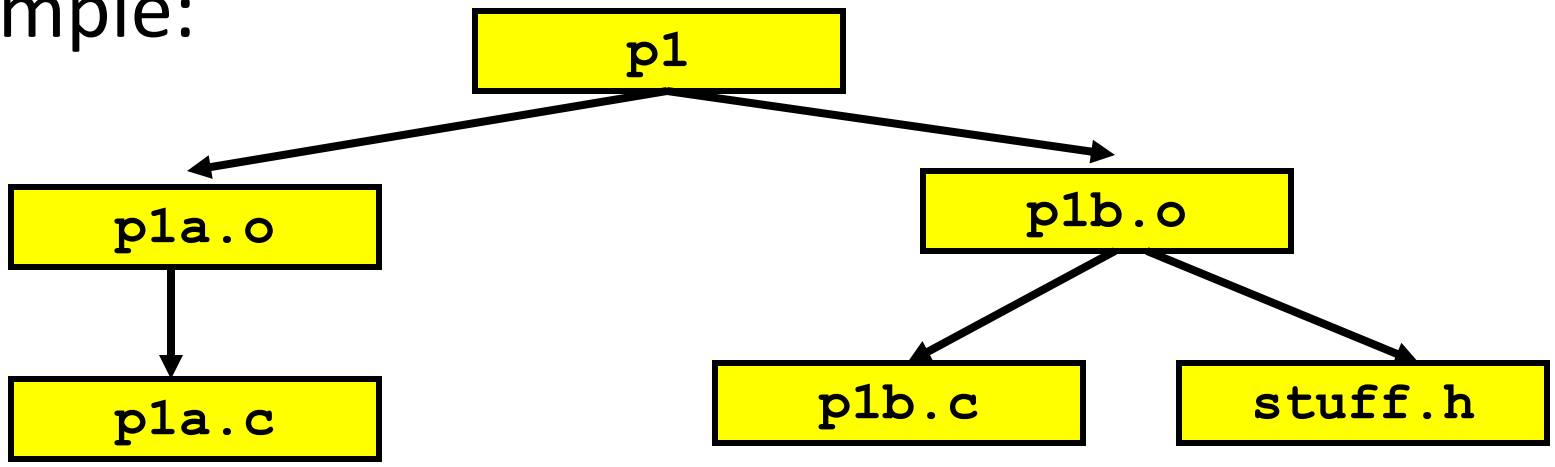
From: http://www.cprogramming.com/tutorial/shared-libraries-linux-gcc.html

Dependency Checking with **`make`**

- Most programming toolsuites (IDEs)…
  - keep track of what files are part of a *project*
  - keeps track of the dependencies between files
  - use this info to "create a new *build*" when files are changed
- **`make`** does the same thing, but under manual control by the programmer
  - dependencies and actions are specified in a **`Makefile`**

…Dependency Checking (cont'd)

- Example:



"p1 depends on p1a.o and p1b.o"

"p1b.o depends on p1b.c and stuff.h"

etc.

Running `make`

- First, create a file (using a text editor) called **`Makefile`**
- After that, any time part of the source code changes, run **`make`** to regenerate executable

```
$ make [-f makefilename] [options] [target]
```

Makefiles

- **`Makefile`** consists of rules of form:

```
target-list: list-of-dependencies-to-check
    list-of-commands-to-execute
```

*There is a **tab** character here – Required! Won't work otherwise!*

Helpful tips

- *blank lines help readability*
- *lines starting with '#' are comments (ignored)*
- *lines can be continued with '\' immediately before newline*

Order of Rules Important

- Order of rules important
  - by default, **`make`** generates the first target in the **`Makefile`**
  - to accomplish something else: **`make target`**
- **`list-of-commands`** can be any executable commands (programs), “shell” commands, etc.

Example

```
# sample Makefile for program p1, which
# consists of just the file p1.c
# Remember: command line *must* start with TAB

p1: p1.c
      gcc -Wall -std=c99 p1.c -o p1 -lm
```

- Means:
  "if **`p1.c`** has changed more recently than the last time the executable **`p1`** was generated, then run **`gcc p1.c`**…"
- i.e., make does the minimum work necessary to regenerate the target

…Example (cont'd)

```
$ make p1
gcc -Wall -std=c99 p1.c -o p1 -lm
$
```

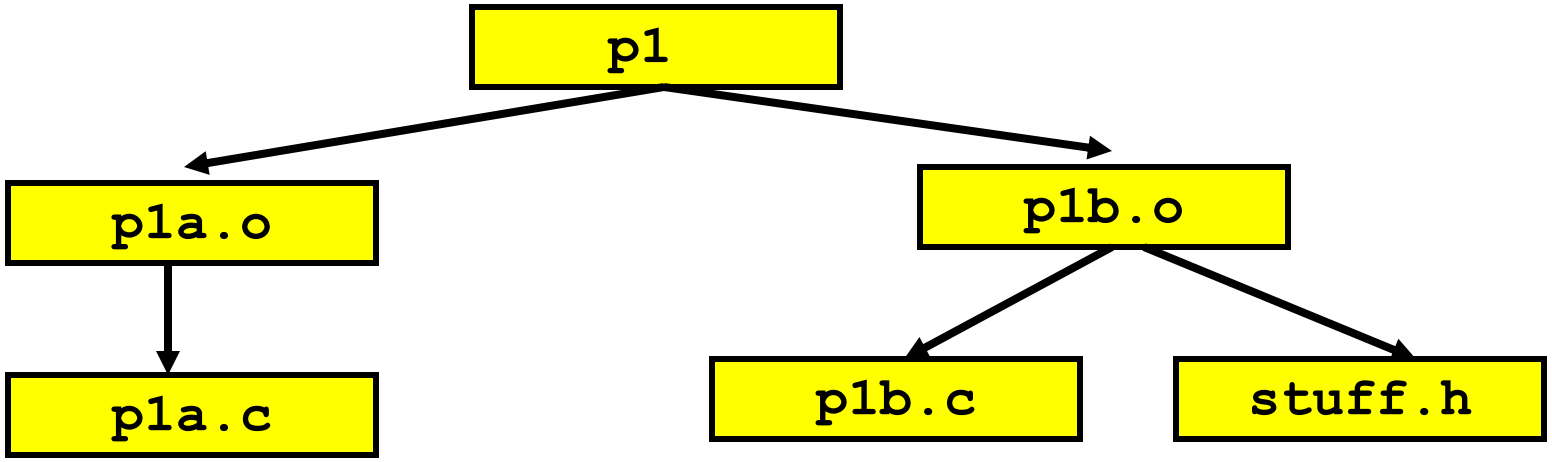
- If **`p1.c`** is less recent than **`p1`**, nothing happens

```
$ make p1
make: 'p1' is up to date.
$
```

Note: to force remake, use ***`touch`*** *command*

```
$ touch p1.c     < sets modification time to now
$ make
gcc -Wall -std=c99 p1.c -o p1 -lm
$
```

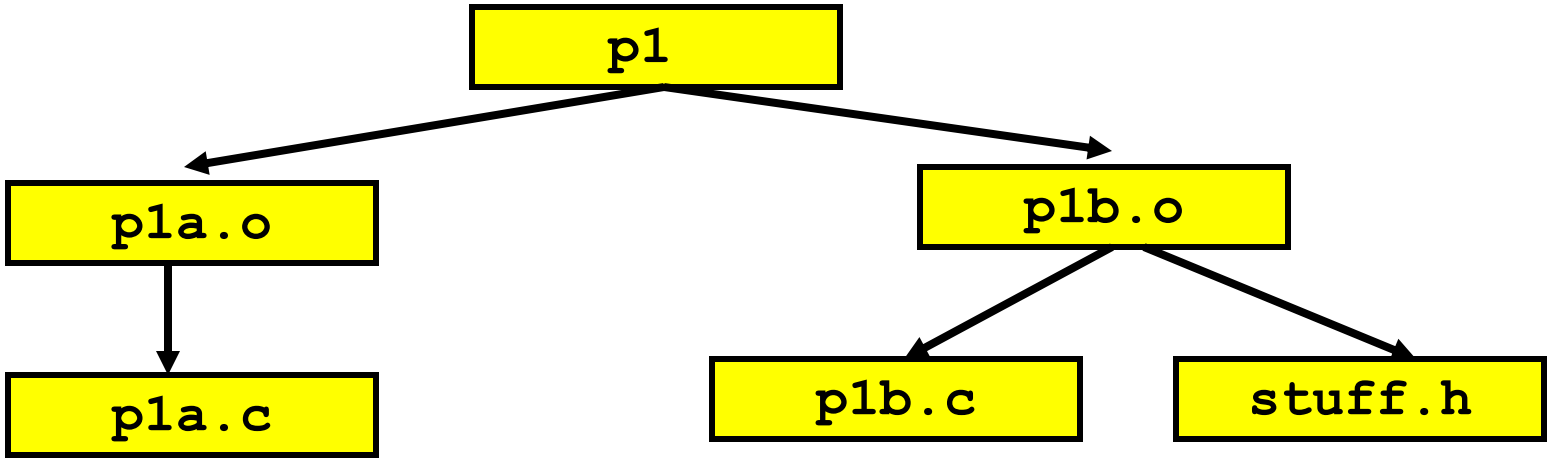
Dependency "Tree" Example



Makefile

```
p1: p1a.o p1b.o
      gcc p1a.o p1b.o -lm -o p1
p1a.o: p1a.c
      gcc -Wall -std=c99 -c p1a.c -o p1a.o
p1b.o: p1b.c stuff.h
      gcc -Wall -std=c99 -c p1b.c -o p1b.o
```

Dependency "Tree" Example



Makefile

```
p1: p1a.o p1b.o
	gcc p1a.o p1b.o -lm -o p1
.c.o:
	gcc -Wall -std=c99 -c $< -o $@
```

Extension rule

Dependency Trees (cont'd)

```
$ make
gcc -Wall -std=c99 -c p1a.c
gcc -Wall -std=c99 -c p1b.c
gcc p1a.o p1b.o -lm -o p1
$
$ vi p1b.c
  ---make some changes to p1b.c---
$ make
gcc -Wall -std=c99 -c p1b.c
gcc p1a.o p1b.o -lm -o p1
$
```

only recompile p1b.c, and link with other object files

Dependency Trees (cont'd)

- The following defeats the purpose of **`make`**
  - what's wrong with this, vs. the previous?

```
p1: p1a.c p1b.c stuff.h
      gcc p1a.c p1b.c -o p1 -lm
```

Automating: Default Rules

- Large set of default (built-in, automatic) dependencies that **`make`** knows about
- Examples:
  - "**`<filename>.o`** usually depends on **`<filename>.c`**"
  - "To regenerate **`<filename>.o`** file, you usually run **`$(CC) <filename>.c -c`**"
- So, for example previously given, almost the complete Makefile is...

```
p1: p1a.o p1b.o
p1b.o: stuff.h
```

…Default (cont'd)

- To see what the complete set of defaults are:

```
$ make -p -f/dev/null
```

- There are a lot of rules…

- Note that these rules are preconfigured to use macro variables CFLAGS, LDFLAGS, CC, etc.

`make` Variables

- Way to assign symbolic names to commands, filenames, and arguments
- Some default variables you can define
  - **`CC`** (default compiler to use)
  - **`CFLAGS`** (default compilation flags)
  - **`LDFLAGS`** (default linking flags)
  - **`TARGET_ARCH`** (target architecture)

…Macros (cont'd)

- Example

```
CC = gcc
CFLAGS = -Wall -std=c99
LDFLAGS = -lm
OBJECTS = p1a.o p1b.o
SOURCES = p1a.c p1b.c
HEADERS = stuff.h

p1: $(OBJECTS)
	$(CC) $(CFLAGS) $(OBJECTS) $(LDFLAGS) -o p1
p1a.o:
p1b.o: stuff.h
```

What's this turn into?

Passing Parameters to **make**

- We can pass macro values to a makefile by specifying them on the command line, e.g.

```
$ make CFLAGS="-O1" PAR2=sw
```

Processes the makefile with **CFLAGS** assigned the value **–O1**, **PAR2** assigned the value **sw**

Referenced in makefile as **$(CFLAGS)**, **$(PAR2)**

Some "Built-In" Macros

Macro	Meaning
`$@`	The current target
`$?`	The list of dependencies (files the target depends on) that have changed more recently than current target
`$*`	The "stem" of filenames that match a pattern
`$<`	The first dependency
`$^`	The list of dependencies

```
p1: $(OBJECTS)
	$(CC) $(OPTIONS) $^ -o $@ -lm
```

Interpretation?

“Dummy” Targets

- Convenient label for a goal, not a file to generate

```
…
p1.tar: Makefile $(HDRS) $(SOURCES)
        tar -uvf $@ $?

clean:
        rm *.o
```

update p1.tar with any of the specified files that have changed more recently than the last time p1.tar was updated

*(Note: **`make`** uses the shell to run stuff,*
*so it understands shell filename expansion, like “**`*.o`**”)*

…"Dummy" (cont'd)

Then you can accomplish that target, e.g.,

```
$ make p1.tar
tar -ucf p1.tar Makefile p1a.c p1b.c stuff.h
…tar output appears here…
$ ---update p1b.c here---
$ make p1.tar
tar -ucf p1.tar p1b.c
…tar output appears here…
$ make clean
rm *.o
$
```

Review the example Makefile

- See the Makefile for the nbody example

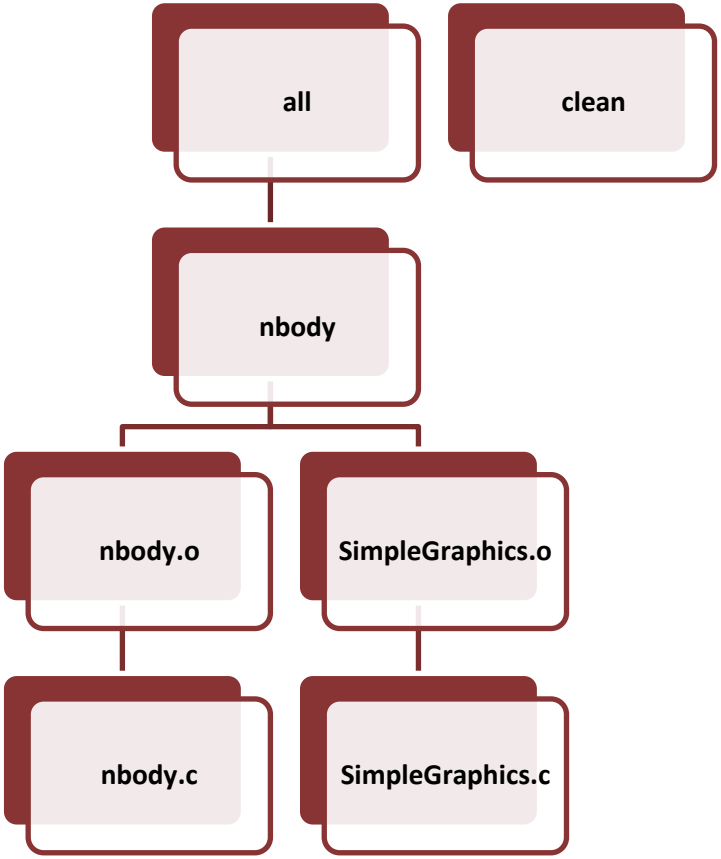
```
CC = gcc
CFLAGS = -Wall -std=c99 -O3 -g
OBJS = nbody.o SimpleGraphics.o

all : nbody

.c.o:
        $(CC) $(CFLAGS) -c $<

nbody : $(OBJS)
        $(CC) $(LIBS) -o $@ $(OBJS)

clean :
        rm -f nbody $(OBJS)
```



Some `make` Command-Line Options

Option	Meaning
`-d`	Print debugging information
`-f file`	Use file instead of Makefile
`-i`	Ignore all errors (i.e., keep going)
`-n`	Print the commands that would be executed, but don't execute them
`-s`	Silent mode; do not print commands, just execute them

Example: compare_sorts (1)…

```
# Makefile to compare sorting routines

BASE     =  /home/barney/progs
CC       =  gcc
CFLAGS   =  -O -Wall
EFILE    =  $(BASE)/bin/compare_sorts
INCLS    =  -I$(LOC)/include
LIBS     =  $(LOC)/lib/g_lib.a \
              $(LOC)/lib/h_lib.a
LOC      =   /usr/local

OBJS     = main.o another_qsort.o chk_order.o \
              compare.o quicksort.o
…
```

…compare_sorts (2)

```
…
$(EFILE): $(OBJS)
	@echo "linking …"
	@$(CC) $(CFLAGS) -o $@ $(OBJS) $(LIBS)

$(OBJS): compare_sorts.h
	$(CC) $(CFLAGS) $(INCLS) -c $*.c

# Clean intermediate files
clean:
	rm *~ $(OBJS)
```

Macro	Meaning
$@	The current target
$?	The list of dependencies (files the target depends on) that have changed more recently than current target
$*	The "stem" of filenames that match a pattern
$^	The list of dependencies

Larger Example: `vi` (1) …

```
PROG= ex
XPG4PROG= ex
XPG6PROG= ex
LIBPROGS= expreserve exrecover
XD4= exobjs.xpg4
XD6= exobjs.xpg6

EXOBJS=       bcopy.o ex.o ex_addr.o ex_cmds.o ex_cmds2.o \
       ex_cmdsub.o ex_data.o ex_extern.o ex_get.o \
       ex_io.o ex_put.o ex_re.o ex_set.o ex_subr.o \
       ex_temp.o ex_tty.o ex_unix.o ex_v.o ex_vadj.o \
       ex_vget.o ex_vmain.o ex_voper.o ex_vops.o \
       ex_vops2.o ex_vops3.o ex_vput.o ex_vwind.o \
       printf.o
EXOBJS_XPG4= $(EXOBJS) compile.o values-xpg4.o
EXOBJS_XPG6= $(EXOBJS) compile.o values-xpg6.o
XPG4EXOBJS= ${EXOBJS_XPG4:%=$(XD4)/%}
XPG6EXOBJS= ${EXOBJS_XPG6:%=$(XD6)/%}
EXRECOVEROBJS=      exrecover.o ex_extern.o
```

…vi (2)…

```
OBJS= $(EXOBJS) $(XPG4EXOBJS) $(XPG6EXOBJS) \
      expreserve.o exrecover.o
SRCS= $(EXOBJS:%.o=%.c) expreserve.c exrecover.c
TXTS = READ_ME makeoptions asfix.c70 ex.news \
       port.mk.370 port.mk.70 port.mk.c70 port.mk.usg \
       ovdoprnt.s ovprintf.c rofix

include ../../Makefile.cmd
#
# For message catalogue files
#
POFILES= $(EXOBJS:%.o=%.po) expreserve.po exrecover.po
POFILE= port.po

# Include all XPG4 and XPG4ONLY changes in the XPG4 version
$(XPG4) := CFLAGS += -DXPG4 -DXPG4ONLY

# Include all XPG4 changes, but don't include XPG4ONLY in the
XPG6 version
$(XPG6) := CFLAGS += -DXPG4 -DXPG6 -I$(SRC)/lib/libc/inc
```

…vi (3) …

```
CPPFLAGS +=   -DUSG -DSTDIO -DVMUNIX -DTABS=8 \
              -DSINGLE -DTAG_STACK
CLOBBERFILES += $(LIBPROGS)
ex :=         LDLIBS += -lmapmalloc -lcurses \
                        $(ZLAZYLOAD) -lgen -lcrypt_i $(ZNOLAZYLOAD)
$(XPG4) :=    LDLIBS += -lmapmalloc -lcurses \
                        $(ZLAZYLOAD) -lgen -lcrypt_i $(ZNOLAZYLOAD)
$(XPG6) :=    LDLIBS += -lmapmalloc -lcurses \
                        $(ZLAZYLOAD) -lgen -lcrypt_i $(ZNOLAZYLOAD)
exrecover :=  LDLIBS += -lmapmalloc -lcrypt_i
lint :=       LDLIBS += -lmapmalloc -lcurses -lgen -lcrypt

ROOTLIBPROGS= $(LIBPROGS:%=$(ROOTLIB)/%)
```

…vi (4) …

```
# hard links to ex
ROOTLINKS= $(ROOTBIN)/vi $(ROOTBIN)/view $(ROOTBIN)/editv \
           $(ROOTBIN)/vedit
ROOTXPG4LINKS= $(ROOTXPG4BIN)/vi $(ROOTXPG4BIN)/view \
               $(ROOTXPG4BIN)/edit $(ROOTXPG4BIN)/vedit
ROOTXPG6LINKS= $(ROOTXPG6BIN)/vi $(ROOTXPG6BIN)/view \
               $(ROOTXPG6BIN)/edit $(ROOTXPG6BIN)/vedit
.KEEP_STATE:

.PARALLEL: $(OBJS)

all: $(PROG) $(XPG4) $(XPG6) $(LIBPROGS)

$(PROG): $(EXOBJS)
        $(LINK.c) $(EXOBJS) -o $@ $(LDLIBS)
        $(POST_PROCESS)
```

…vi (5)…

```
…
$(XD4)/compile.o $(XD6)/compile.o: ../../expr/compile.c
	$(COMPILE.c) -o $@ ../../expr/compile.c
…
$(XD4):
	-@mkdir -p $@
…
install: all $(ROOTPROG) $(ROOTLIBPROGS) $(ROOTLINKS) \
	$(ROOTXPG4PROG) $(ROOTXPG4LINKS) $(ROOTXPG6PROG) \
	 $(ROOTXPG6LINKS)
…
clean:
	$(RM) $(OBJS)

lint: lint_SRCS
```

`Autoconf` and `Automake`

- **`autoconf`** automates the setting of options which are system configuration-dependent
- **`automake`** automates the generation of large **`Makefiles`**
- Details for another day...