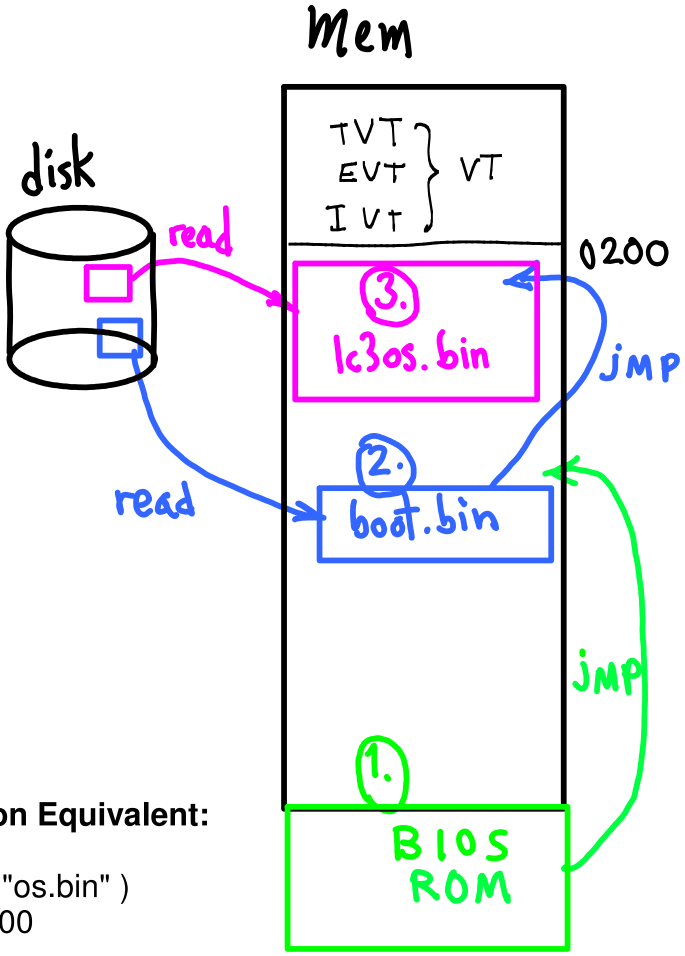
LC3 OS basics

LC3 System Start-Up Assumptions
We will write an OS for the LC3.
What would a real LC3 do at start up?

1. BIOS execution
--- PC points to BIOS (Basic IO System).
--- POST: Test and initialize hardware.
--- BOOT: Read disk block 0 (512B);
--- BOOT: Store boot block at x3000;
--- BOOT: JMP x3000.

2. Booter execution
--- Read OS disk blocks, load at x0200,
--- JMP x0200

3. OS execution (JMP)
--- OS code begins execution at x0200.



Our Simulation Equivalent:

-- readmemb("os.bin")
-- PC <== x0200

Init OS

OS code intialization
(interrupts are disabled: PSR.Priority == 7)

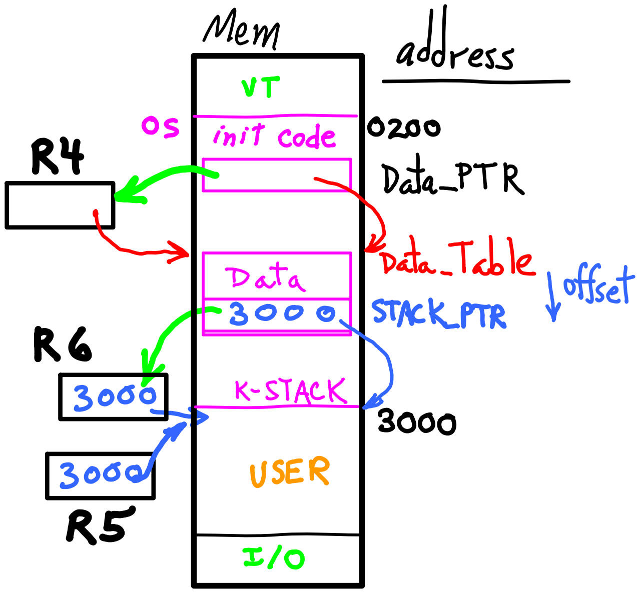
-- **set Supervisor's GDP (R4) SP (R6) BP (R4)**
Note: can't use subroutines until SP is set up.

-- **set up VT**
Note: can't use traps until VT is set up.
Initialize service routines, e.g.,
JSR kbInt_init_BEGIN

-- **turn on INTs**, PSR.priority <== 3'b000

-- **jump to OS command loop (also, service INTs)**

```
while( 1 ) {
        display_prompt();
        command = get_response();
        switch (command) {
            case "r": do_run(); break;
            case "q": do_quit(); break;
            case "h": do_help(); break;
        }
}
```



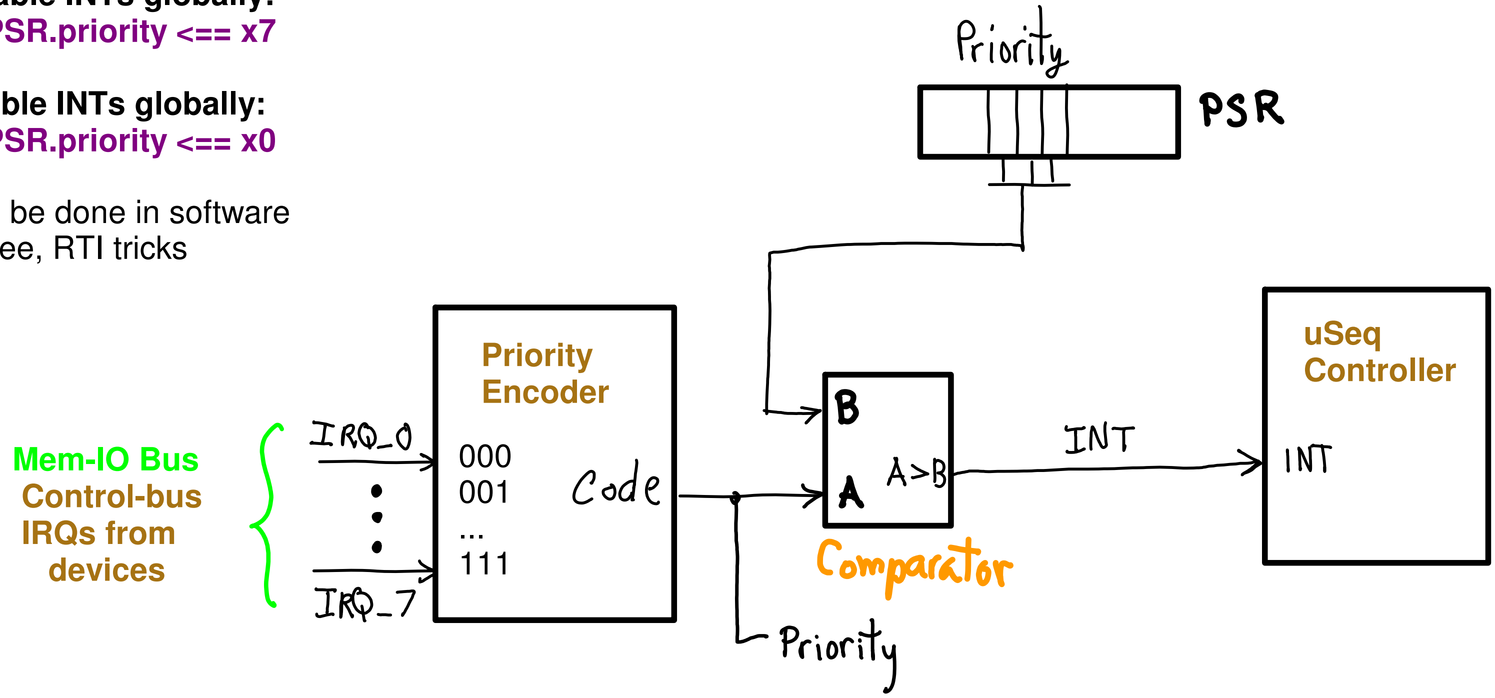
;---- OS initialization, Set up GDP, SP, BP

```
LEA R4, Data_PTR
LDR R4, R4, #0
LDR R6, R4, #(offset to Stack_PTR)
ADD R5, R6, #0

Data_PTR:    .FILL   Data_Table
```

Disable INTs globally:
--- PSR.priority <== x7

Enable INTs globally:
--- PSR.priority <== x0

Can be done in software
--- see, RTI tricks



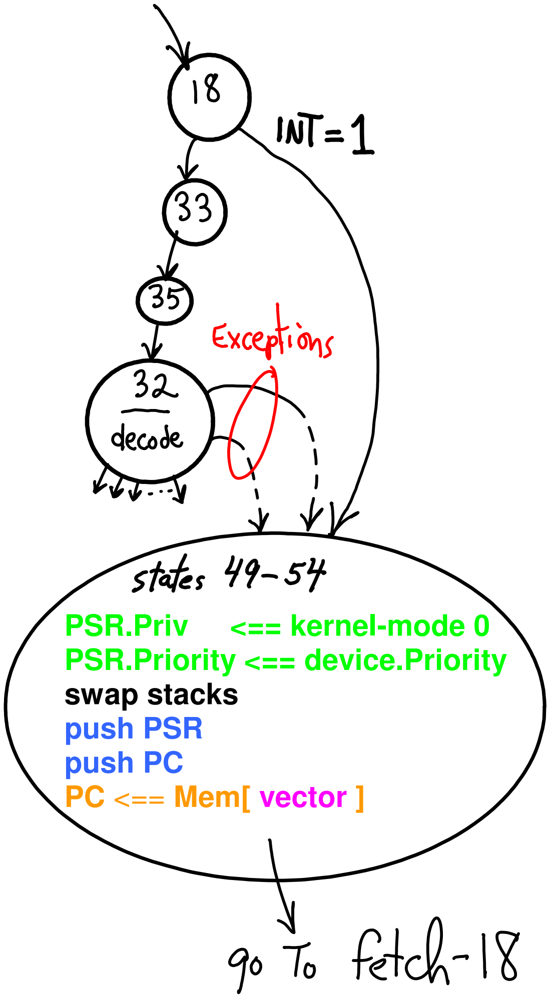
Mem-IO Bus
Control-bus
IRQs from
devices

Priority
Encoder

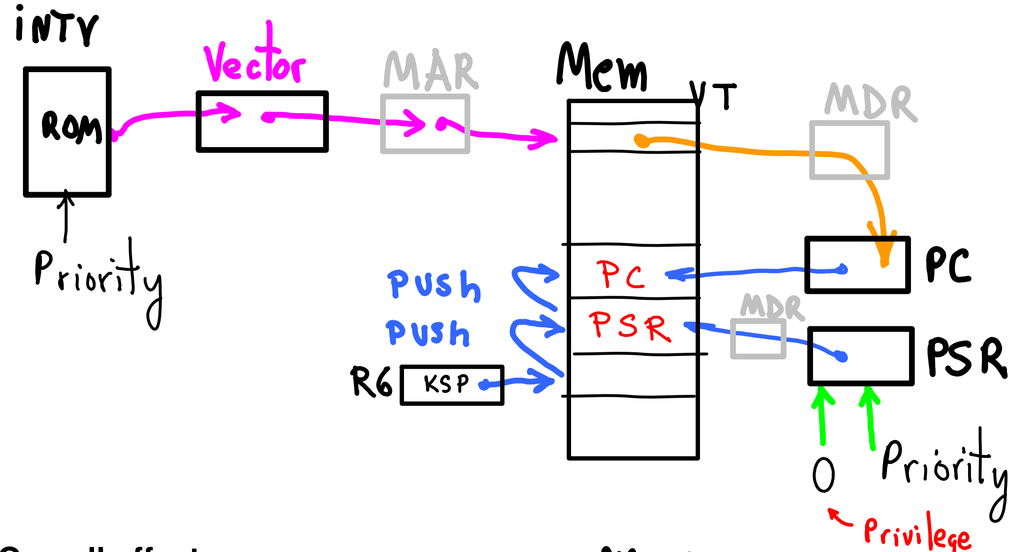
000
001
...
111

uSeq
Controller

--- I/O device i sets **IRQ_i = 1**.
--- Highest priority goes to comparator.
--- **If (Code > PSR.priority)**
------ **INT <== 1**
------ **uSeq branches from state 18 to 49**
------ **uSeq saves state,**
------ **jumps via VT**
------ handler **jumps back via RTI** execution.



PSR.Priv <== kernel-mode 0
PSR.Priority <== device.Priority
swap stacks
push PSR
push PC
PC <== Mem[vector]

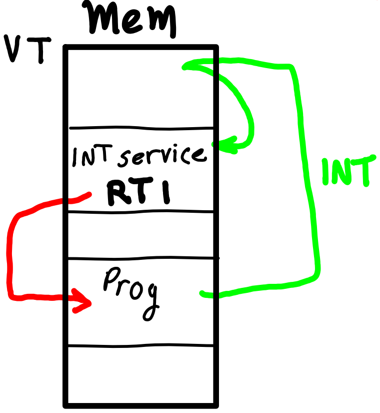


Overall effect:

--- **Save** program's state,
Jump to service routine

--- **Service** the INT request

--- **Restore** program's state
Jump back to instruction



Note:

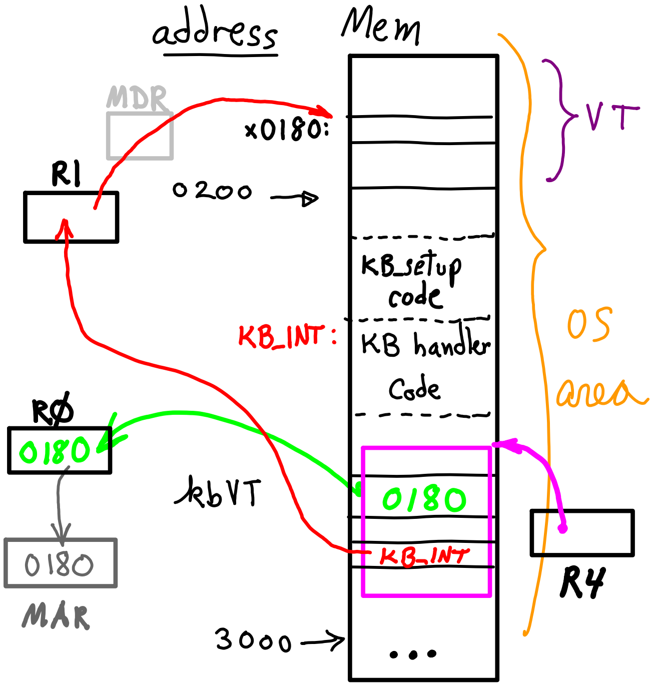
kernel = supervisor
ksp = SSP

Init the Service Routine

Each service has its own init. routine

```
KB_setup :      ;---- init the KB interrupt handler

                        ;----------- set up VT for kb
LDR R0, R4, #(KB_VT)   ;--  R0 <== pointer to VT slot.
LDR R1, R4, #(KB_int)   ;--  R1 <== pointer to KB handler
STR R1, R0, #0          ;-- Mem[R0] <== R1
...                     ;-- ...
JMP R7                  ;-- return from KB_setup
```

```
KB_int :   ;---------------- KB interrupt handler ----

 push__( R7)   ;--- save registers
  ...          ;-- handle KB interrupt: get char, ...
  pop__( R7)   ;--- restore registers
  RTI
```

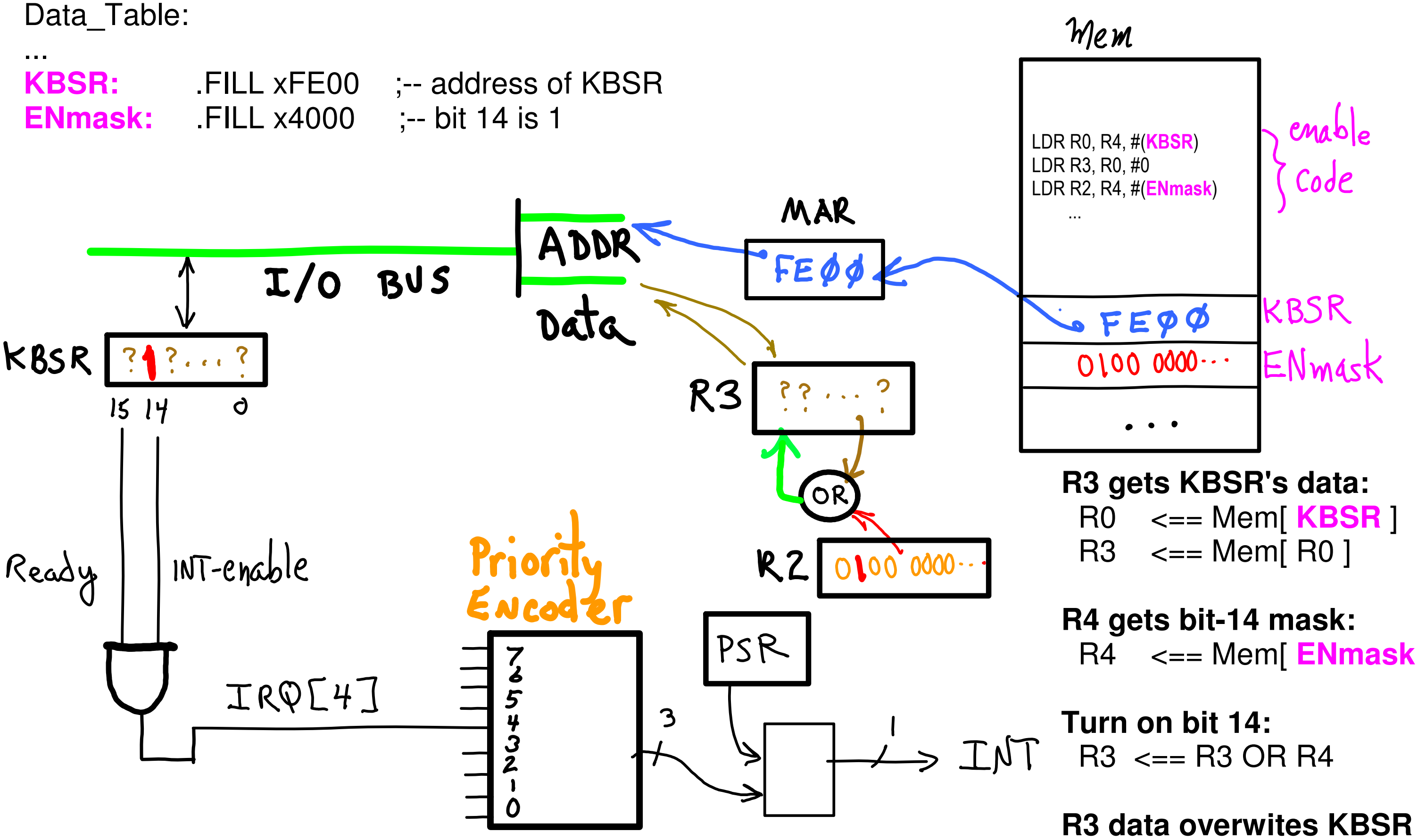


```
;--------- Enable KB interrupts (turn on bit 14)

 LDR R0, R4, #(KBSR)     ;-- R0 <== pointer to KBSR.
 LDR R3, R0, #0          ;-- R3 <== content of KBSR.
 LDR R2, R4, #(ENmask)   ;-- R4 <== enable mask.
 ... ?                   ;-- R2 <== OR( R3, R4)
 STR R2, R0, #(KBSR)     ;-- KBSR <== R2
 ...
```

See symbol table for value of "KB_int", it's an address.

f.asm → lc3as → f.out
f.sym (symbol table)

```
Data_Table:
...
KBSR:     .FILL xFE00    ;-- address of KBSR
ENmask:   .FILL x4000    ;-- bit 14 is 1
```



R3 gets KBSR's data:
R0 <== Mem[KBSR]
R3 <== Mem[R0]

R4 gets bit-14 mask:
R4 <== Mem[ENmask]

Turn on bit 14:
R3 <== R3 OR R4

R3 data overwites KBSR data

Pre-processing

OR(R_1, R_2, R_3) in LC3 ISA

$$R1 \leftarrow x + y = \overline{\left\{\overline{x + y}\right\}} = \overline{\left\{\bar{x} \cdot \bar{y}\right\}}$$

De Morgan's Law

$R2 \leftarrow \bar{x}$ NOT R2, R2

$R3 \leftarrow \bar{y}$ NOT R3, R3

$R1 \leftarrow \bar{x} \cdot \bar{y}$ AND R1, R2, R3

$R1 \leftarrow \overline{\left\{\bar{x} \cdot \bar{y}\right\}}$ NOT R1, R1

restore args? →

NOT R2, R2

NOT R3, R3

Simple substitution

```
.ORIG x0200
 ADD SP__, SP__, #-1
.END
```

SP__ Don't confuse with other strings: SPELL → R6ELL

```
cat foo.asm | sed -e ' s/SP__/R6/ ' > foo_pre.asm
```

```
.ORIG x0200
ADD R6, SP__, #-1
.END
```

```
cat foo.asm | sed -e ' s/SP__/R6/g ' > foo_pre.asm
```

```
.ORIG x0200
ADD R6, R6, #-1
.END
```

Arguments

```
cat foo.asm | sed -f  sed_defs > foo_pre.asm
```

```
s/SP__/R6/g
```

```
.ORIG x0200
push__(R4)
.END
```

```
cat m_defs foo.asm | m4 > foo_pre.asm
```

back quote

```
define(`push__', `
    add R6, R6, -1
    str $1, R6, 0')dnl
```

```
.ORIG x0200
    add R6, R6, -1
    str R4, R6, 0
.END
```

Pre-processing for data offsets in global data table

```
LDR R0, R4, #1
LDR R1, R4, #4
```

what are these?
what do they refer to?

Easier to read?

```
LDR R0, GDP__,  #KBSR__ )
LDR R1, GDP__,  #Mask15__ )
```

```
   ...

Data_Table:
 .FILL x0000   ;-- VAR foo__        (0)
 .FILL xFE00   ;-- PTR  KBSR__      (1)
 .FILL x5678   ;-- PTR  bar__       (3)
 .FILL x9ABC   ;-- PTR  fubar__     (4)
 .FILL x8000   ;-- VAL  Mask15__    (5)
 .FILL x4000   ;-- VAL  Mask14__    (6)
```

```
s/GDP__/R4/g
s/foo__/0/g
s/KBSR__/1/g
s/bar__/2/g
s/fubar__/3/g
s/Mask15__/4/g
s/Mask14__/5/g
```

sed command file

OR

m4 command file

```
define(`GDP__',  `R4')dnl
define(`foo__',  `0')dnl
   ...
```

JSR, TRAP?

m4 does substition for args

```
JSR__( KB_setup__ , R0, L1 )

     ...

Data_Table:
 .FILL x0000        ;-- VAR foo__          (0)
 .FILL x5678        ;-- VAL bar__          (1)
 .FILL KB_setup     ;-- PTR KB_setup__     (2)
```

foo.asm

```
JSR__( 2 , R0, L1 )
```

```
LDR R0, R4,  #2
LEA R7, L1
JMP R0
L1:
```

foo_pre.asm

```
define(`GDP__',  `R4')dnl
define(`foo__',  `0')dnl
define(`bar__',  `1')dnl
define(`KB_setup__',  `2')dnl
define(`JSR__', `
    LDR $2, GDP__, #$1
    LEA R7, $3
    JMP $2
    $3:')dnl
```

m

cat m foo.asm | m4 > foo_pre.asm

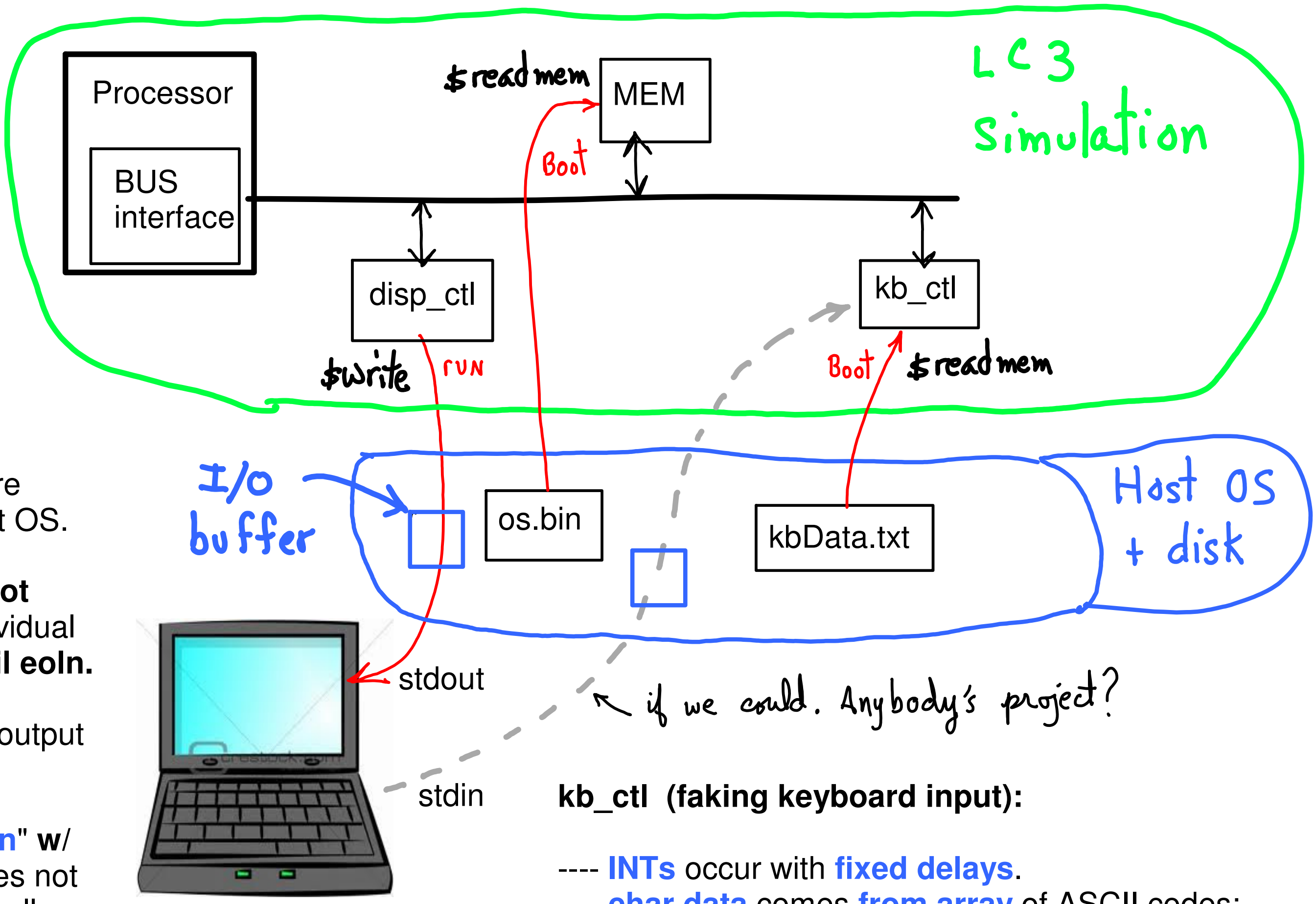
```
TRAP__( x25__ , R0, L2)

Data_Table:
 .FILL x0000  ;-- VAR   foo__    (0)
 .FILL x0025  ;-- VAL   x25__    (1)
```

```
define(`x25__',  `1')dnl
define(`TRAP__', `
    LDR $2, GDP__,  #$1
    LDR $2, $2, #0
    LEA R7, $3
    JMP $2
    $3:')dnl
```

```
LDR R0, R4, #1
LDR R0, R0, #0
LEA R7, L2
JMP R0
L2:
```

Environment

Simulated device controllers could communicate with host system's physical devices through host OS's file system and disk. Execute a second process, "kb.c".



stdin, stdout are **buffered** in host OS.

stdout buffer not flushed for individual char output **until eoln.**

Delays seeing output from LC3.

Have to **send** "**/n**" **w/ each char**? Does not look good. Oh well.

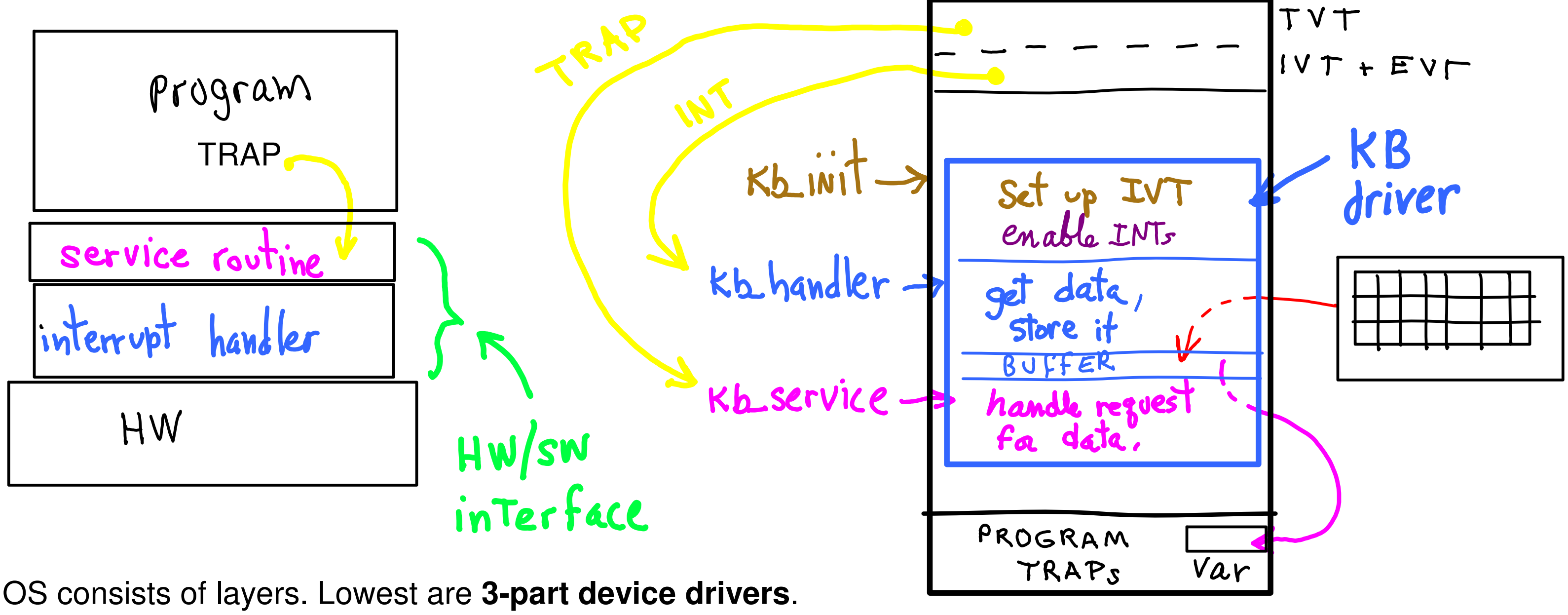
kb_ctl (faking keyboard input):

---- **INTs** occur with **fixed delays**.
---- **char data** comes **from array** of ASCII codes:

[x21, x22, x23, ... ,] == [; # $ ...]

--- **readmemb()** **initializes array at boot**.

LC3 OS structure, Low



OS consists of layers. Lowest are **3-part device drivers**.
(1) **init**, set IVT addresses, etc. (2) **interrupt handler** responds to HW device, buffers data (3) **service routine** handles requests from higher-level software (OS or user) to send data to program's memory area.

(using m4 pre-process: m4 macro def's cat here)

```
    .ORIG x0200

    GDP_init__(DATA)
    GO_TO_ENTRY__( CODE )
```

setup GDP

```
DATA:
    .FILL x3000      define(`STACK_addr__',   `0')dnl
    .FILL x0021      define(`PUTC_vect__      `1')dnl
    .FILL PUTC_init  define(`PUTC_init__',    `2')dnl
    .FILL PUTC_srvc  define(`PUTC_srvc__',    `3')dnl
```

DATA SEGMENT

define offset w/ data

```
CODE:
    LDR SP__, GDP__, #STACK_addr__
    LDR BP__, GDP__, #STACK_addr__
```

CODE SEGMENT

set up STACK

```
    JSR__( PUTC_init__, R0, L1)
    JSR__( GETC_init__, R0, L2)
```

set up IVT

```
    TRAP__( PUTC_srvc__ , R0, L3)
    ...
```

use a service

Turn on INTs

Go To Main Loop

```
PUTC_init:
    JMP R7
PUTC_srvc:
    JMP R7
```

A service

init:
handler:
service:

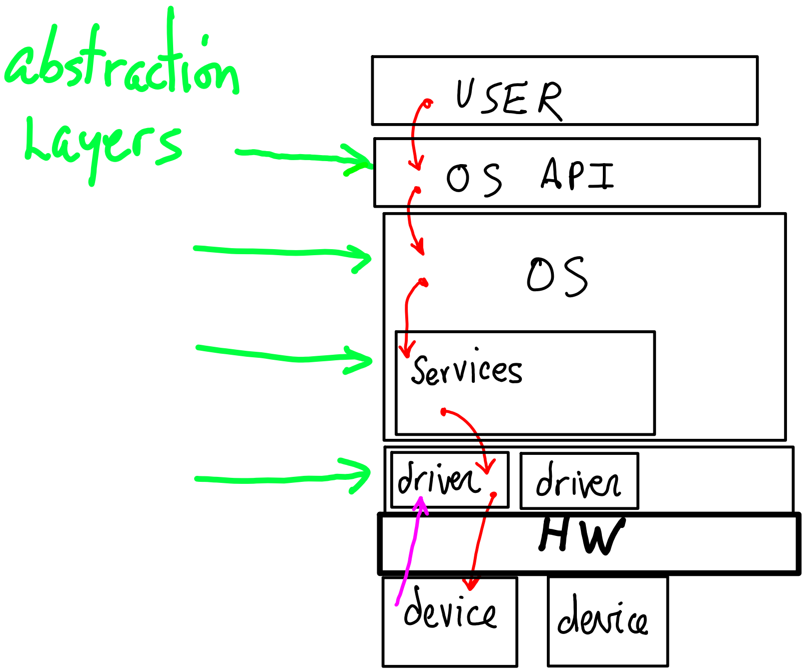
device drivers
print services
network services
...

Hierarchical OS

Low-level:
- basic abstract interface
- -- read, write

Mid-level
- built on low-level
- abstract structures
- -- pages, disk blocks
- -- buffers, connections
- -- data structures
- -- queuing

Higher-level
- -- files, documents
- -- pipes, streams
- -- objects, remote/local
- -- RPC, RMI
- -- policies, scheduling



load m4 defs and process w/ m4

cat m4-defs foo.asm | m4 > foo_pre.asm

m4 defs

```
changecom(`;')

define(`GO_TO_ENTRY__', `  ;-- GO_TO_ENTRY__( CODE )
   LEA R7, $1_PTR          ;--   LEA R7, CODE_PTR       ;-- R7 points.
   LDR R7, R7, #0          ;--   LDR R7, R7, #0         ;-- R7 gets addr.
   JMP R7                  ;--   JMP R7                 ;-- go to CODE.
   $1_PTR: .FILL $1')dnl   ;--   CODE_PTR: .FILL CODE   ;-- data.

define(`GDP__',`R4')dnl    ;-- GDP__ == R4
define(`BP__' ,`R5')dnl    ;-- BP__  == R5
define(`SP__' ,`R6')dnl    ;-- SP__  == R6

define(`GDP_init__', `     ;-- GDP_init__( Table )
   LEA GDP__, $1_PTR       ;--   LEA GDP__, Table_PTR   ;-- GDP points.
   LDR GDP__, GDP__, #0    ;--   LDR GDP__, GDP__, #0   ;-- GDP gets addr.
   BR  init_GDP_done       ;--   BR  init_GDP_done      ;-- jump over,
   $1_PTR: .FILL $1        ;--   Table_PTR: .FILL Table ;--      data,
   init_GDP_done: ')dnl    ;--   init_GDP_done:         ;--         to here.

define(`JSR__', `          ;-- JSR__( func__, R0, L1 )
   LDR $2, GDP__, #$1      ;--   LDR R0, GDP__, #func__    ;-- R0 gets addr
   LEA R7, $3              ;--   LEA R7, L1                ;-- linkage
   JMP $2                  ;--   JMP R0                    ;-- call
   $3:')dnl                ;--   L1:                       ;-- return here

define(`TRAP__', `         ;-- TRAP__(vect__, R0, L2)
   LDR $2, GDP__, #$1      ;--   LDR R0, GDP__, #vect__    ;-- R0 aimed at VT
   LDR $2, $2, #0          ;--   LDR R0, R0, #0            ;-- R0 gets addr
   LEA R7, $3              ;--   LEA R7, L2                ;-- linkage
   JMP $2                  ;--   JMP R0                    ;-- call
   $3:')dnl                      L2:                       ;-- return here

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; m4-test.asm
;;
;; test our m4-commands as a preprocessor.
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

   .ORIG x0200

   GDP_init__(DATA)
   GO_TO_ENTRY__( CODE )

DATA:
   .FILL x3000     define(`STACK_addr__',       `0')dnl
   .FILL x0021     define(`PUTC_vect__',        `1')dnl
   .FILL PUTC_init define(`PUTC_init__',        `2')dnl

CODE:
   LDR SP__, GDP__, #STACK_addr__
   LDR BP__, GDP__, #STACK_addr__

   JSR__( KB_setup__, R0, L2)
   TRAP__(x25__ , R0, L1)

KB_setup:
   JMP R7
```

foo.asm
starts here

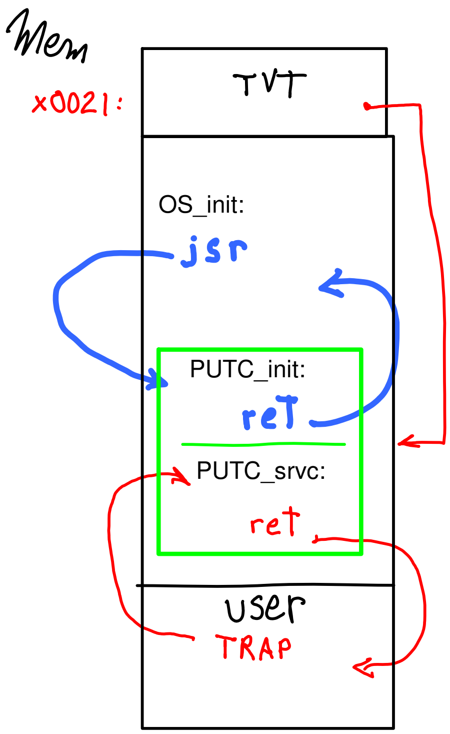
Aside: stripping out blank space after pre-processing.
cat m4-def

OS Layers

Modular development

Module consist of two parts:
--- PUTC_init
    Called (JSR) by OS init.
    Return via "RET", "JMP R7".
--- PUTC_srvc
    Called via TRAP
    Returns via RET.

```
;--------------------------------------
;-- putc.asm, a module
;--------------------------------------
  ;=====================================================
  ;-- .CODE
  ;-------------------------------------------------------
  PUTC_init:
    ldr r0, GDP__, #PUTC_vect ;-- r0 <== slot addr
    ldr r1, GDP__, #PUTC_srvc ;-- r1 <== svc addr
    str r1, r0, #0            ;-- IVT[r0] <== svc addr
    ret

  ;;;===================================================
  ;;;-- PUTC_srvc() - trap x21:  R0 == char
  ;-------------------------------------------------------
  PUTC_srvc: ;-----------------------------------------
    putc_POLL:                ;-- do
      ...                     ;--    status <== DSR
      BRzp putc_POLL          ;-- until(status == READY)
    ...                       ;-- DDR <== char (print char)
  ret
  ;-------------------------------------------------------
  ;;;===================================================
  ;;;-- .DATA
  ;-------------------------------------------------------
  DSR:              .FILL xFE04  ;-- display status
  DDR:              .FILL xFE06  ;-- display data
  DSR_READY_MASK:   .FILL x8000  ;-- DSR[15]=1?
```

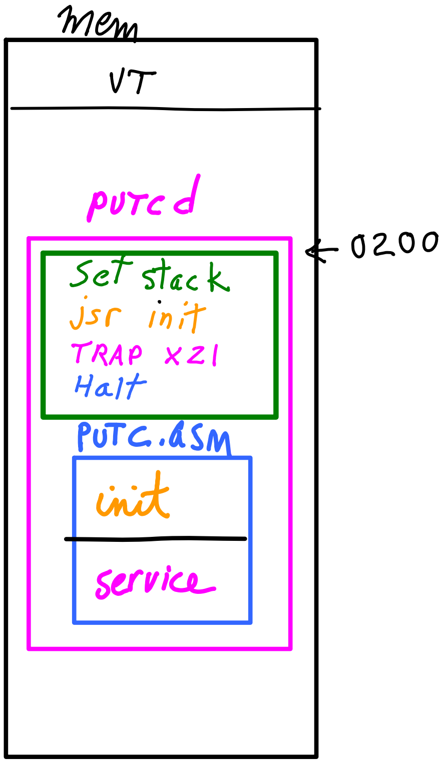


module is linked to OS
- via source code, or
- via link editing

wouldn't it be nice if...

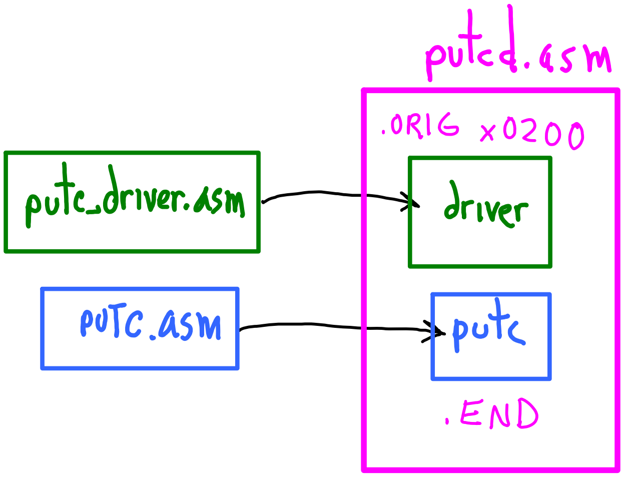
TESTING, independent of OS code

```
;--------------------------------------
;-- putc_driver.asm
;--------------------------------------
 ;-- set GDP
 ;-- Set stack.
 ;-- init putc
 ;-- arg <== MY_CHAR
 ;-- trap( arg )
 done:
 ;-- R4  <== STOP_CLOCK
 ;-- MCR <== R4  (halts LC3)
 ;;--- .DATA ------------------------------
 STOP_CLOCK:    .FILL x8000  ;-- MCR[15]=1
 MCR:           .FILL xFFFE  ;-- mach. ctl reg
 MY_CHAR:       .FILL x0041  ;-- ASCII 'A'
```



Build & Run

1. edit



2. Pre-process, assemble, convert, copy to ../run

has both sed and m4 defs (?)

```
% make os.bin OS=putcd

  cat   m4-defs putcd.asm  |  m4  >  putcd_pre.asm

  lc3as   putcd_pre.asm

  cat   putcd_pre.obj  |  obj2bin  |  sed '1d'  >  putcd_pre.bin

  cp   putcd_pre.bin   ../run/putcd.bin
```

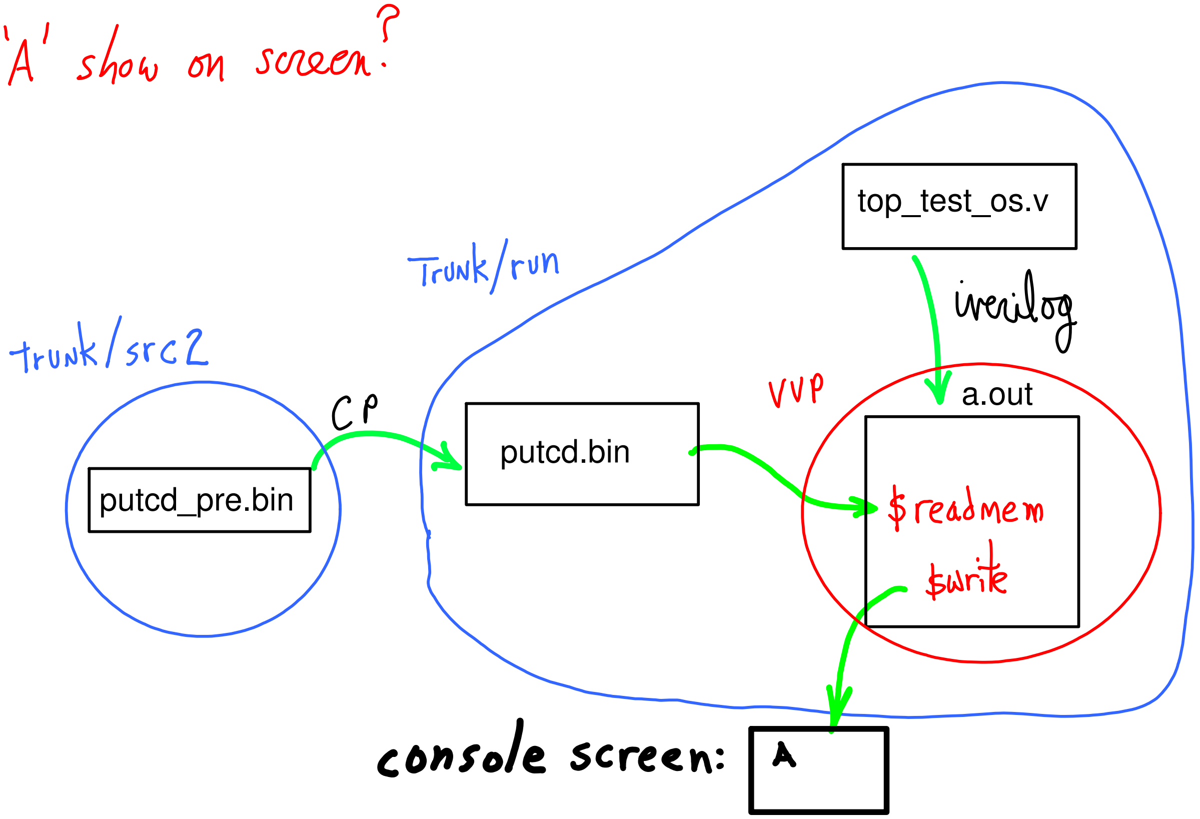
```
cat   putcd.asm  |  lc3pre  >  putcd_pre.asm
```

if using PennSim, stop here

3. Run does 'A' show on screen?

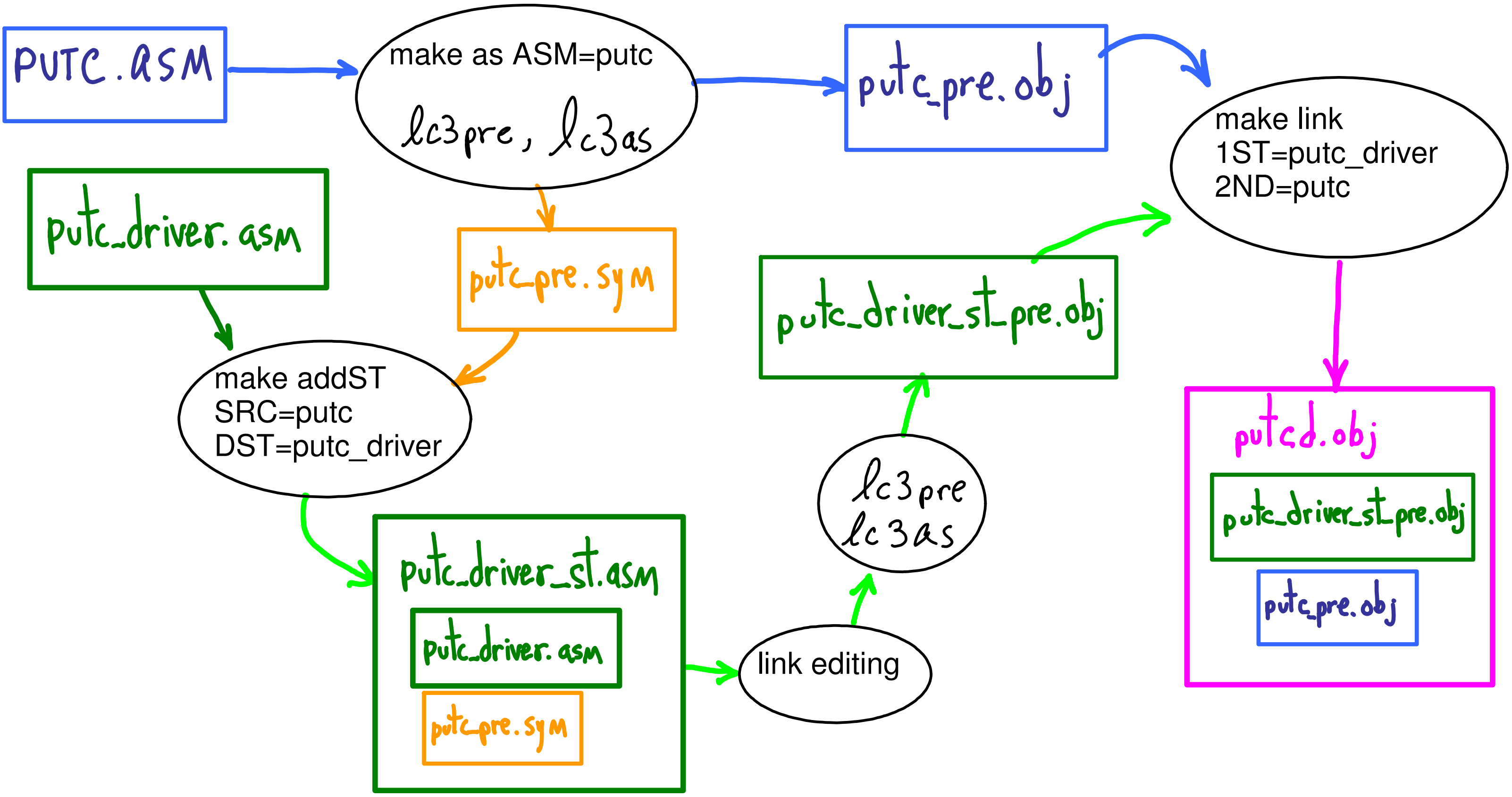
cd ../run

vvp a.out



Aside: link editor ?

First Try:
Edit .asm source code. Concatenate .obj files.
Need symbol table to adjust addresses.



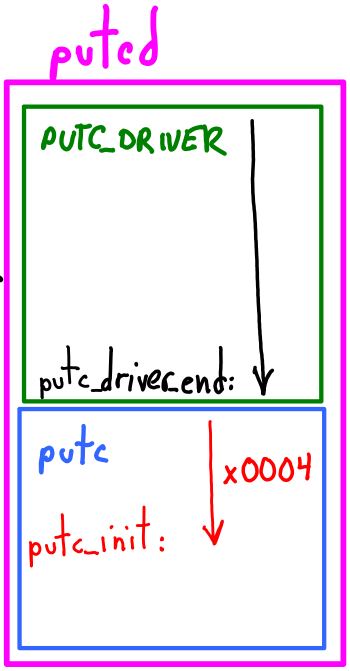
```
;-----------------------------------------
;-- putc_driver.asm
;-----------------------------------------
        .ORIG x0200
      . . .
   LDR R1, GDP, #driver_end__
   LDR R2, GDP, #putc_init___ )
   ADD R2, R2, R2
   JSRR R2
     ...
 .FILL 0    ;-- putc_init
 .FILL driver_end
driver_end:
        .END
// putc.asm Symbol table
// Scope level 0:
//    Symbol Name          Page Address
//    ----------------     ------------
//    putc_init            0004
//    putc_init_END        0007
//    putc_svc             0007
//    putc_POLL            000B
//    end_putc_POLL        000F
//    putc_END             0012
//    PUTC_TVT_LOC         0018
//    DSR                  0019
//    DDR                  001A
//    DSR_READY_MASK       001B
//    END                  001C
```

} JUMP To putc_init

run Time

link edit Time

copy



putc_driver_end: ==
size_of(**putc_driver**)

x0004 ==
offset to putc_init
relative to start of **putc**

putc_driver_end + x0004 ==
address of **putc_init**

EDITING: **Copy** the value of

putc_init

from **symbol table** to

.FILL 0

---- lables need to be identified
.external putc_init

C? assumes

---- handle data references similarly

---- next step: **edit .obj files** instead of .asm
need each .obj to **include its symbol table**
need table to identify **where to edit**

Advantages of linking

1. Code kept **separate, independent**

2. **Test** module **once, reuse** as tested component

3. Compile/Assemble separately, **smaller builds** (Make, avoid re-compile/re-assemble

Link methods

1. **by hand**: include **all source code** into one unit, then **hand edit** to fix.

2. **linker**: **write an .obj linker**

3. **C compiler**: it **includes a linker** (and a pre-processor)

Write LC3 assembly (main.asm, foo.asm)
---- Use lcc C conventions
---- rename to match lcc (main.lcc, foo.lcc)
---- let lcc do the linking for you:

```
lcc main.lcc foo.lcc
```

.OBJ linking Advantages:
--- separate module development: **name independence**
--- **partial builds** w/ linking (what Make is really for)
--- easy to **link C w/ assembly**
--- **stack discipline:** **reentrant code, multiple threads**

(see trunk/src/lcc_annotate)

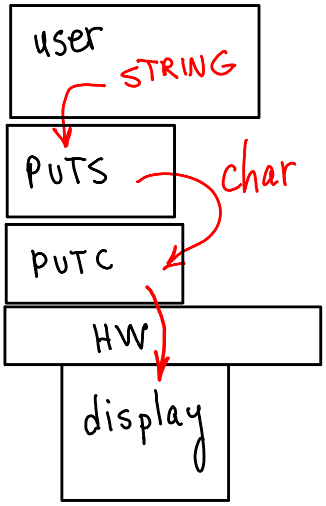
$$\text{lcc -c foo.c} \Rightarrow \underbrace{\text{foo.lcc}}_{\text{assembly}}$$

$$\text{lcc foo.c} \Rightarrow \left\{\begin{array}{l} \text{a.asm} \\ \text{a.sym} \\ \text{a.obj} \end{array}\right.$$

OS, 2ND layer user service

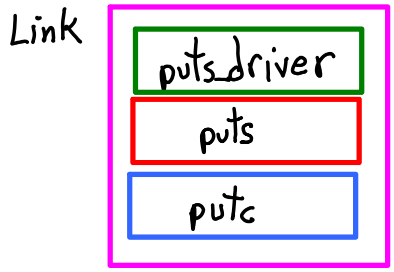
2nd layer service
  uses 1st layer abstraction.

print a string to display.



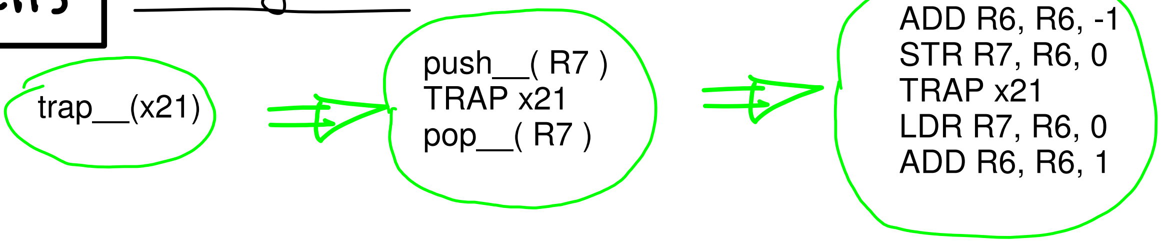
```
;-------------------------------------
;-- puts.asm
;-------------------------------------
;.CODE
  ;;;=========================================
  ;;;-- puts_init
  ;-----------------------------------------
     ...

  ;;;=========================================
  ;;;-- puts- trap x22:
  ;;;-- Display string, R0 == address
  ;-----------------------------------------
  puts_BEGIN: ;------------------------------
    push__( R7 )        Save R7

    mov__( R1, R0 )                ;-- R1 <== char_ptr
    LDR R0, R1, 0                  ;-- char <== *char_ptr

    while_nonNUL:                  ;-- begin_while
      BRz end_puts_while           ;-- until( char == NUL )
      TRAP x21                     ;--   call putc
      ADD R1, R1, 1                ;--   char_ptr++
      LDR R0, R1, 0                ;--   char <== *char_ptr
      BR while_nonNUL              ;--
    end_puts_while:                ;-- end_while

    pop__( R7 )
    JMP R7                         ;-- RET
```

Test same as putc



Nested Calls

Saving R7

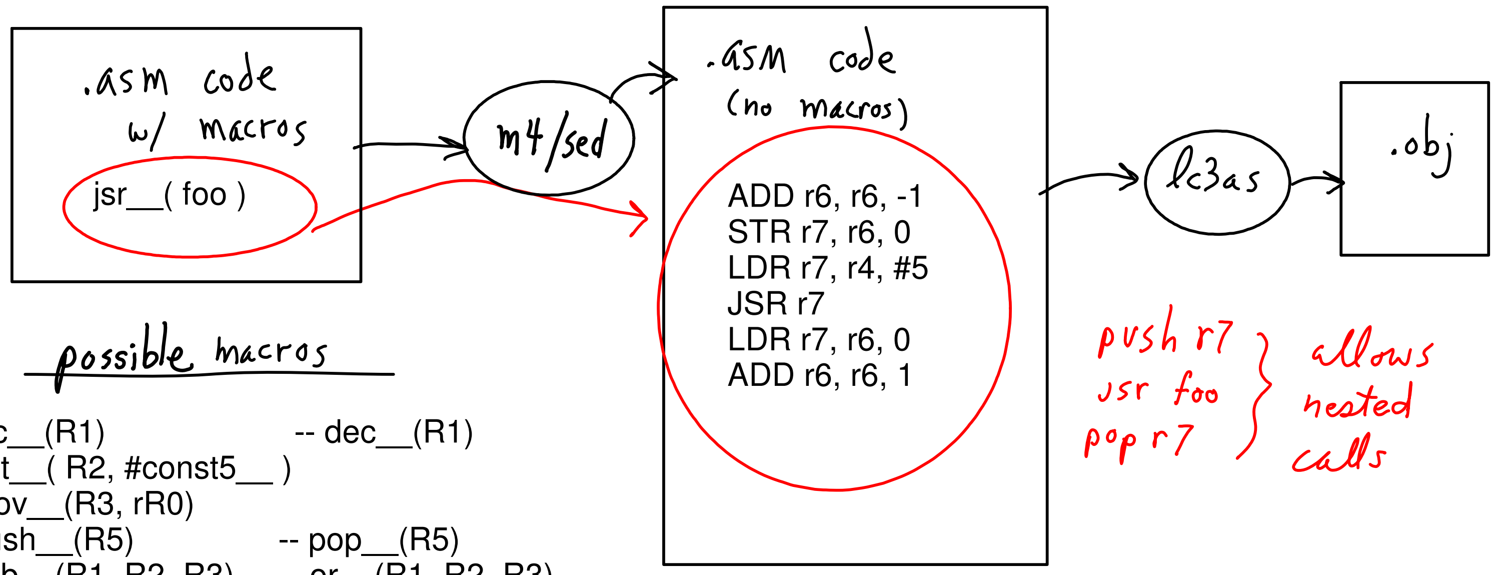


```
trap__(x21)
```

```
push__( R7 )
TRAP x21
pop__( R7 )
```

```
ADD R6, R6, -1
STR R7, R6, 0
TRAP x21
LDR R7, R6, 0
ADD R6, R6, 1
```

In general, may need to save ALL registers.
  ===> CALLEE SAVE (called code save registers)
  ===> CALLER SAVE (code that makes the call saves its own registers



```
ADD r6, r6, -1
STR r7, r6, 0
LDR r7, r4, #5
JSR r7
LDR r7, r6, 0
ADD r6, r6, 1
```

possible macros

```
-- inc__(R1)                -- dec__(R1)
-- set__( R2, #const5__ )
-- mov__(R3, rR0)
-- push__(R5)              -- pop__(R5)
-- sub__(R1, R2, R3)       -- or__(R1, R2, R3)
-- jsr__( #mySub__)         -- trap__(x13)
-- getc__                  -- putc__
-- halt__                  -- puts__
-- intsOff__                  intsOn__
```

aka, pseudo-instructions

Provides mechanism for nested calls/recursion

All macros have "__" double underscore

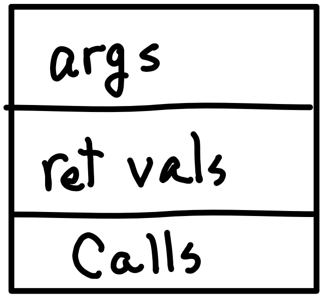
Condition codes are set as expected

Argument registers are unchanged, only destination changes

example	translation
mov__(R3, R5)	ADD R3, R5, 0
zero__(R2)	AND R2, R2, 0
inc__(R7)	ADD R7, R7, 1
push__(R5)	dec__(SP__) STR R5, SP__, 0
pop__(R5)	LDR R5, SP__, 0 inc__(SP__) mov__(R5, R5) ;;-- sets NZP CCs

sub__(R1, R2, R3)	not__(R3)
	inc__(R3)
	ADD R1, R2, R3
	dec__(R3)
	not__(R3) ;;-- R2, R3 unchanged,
	mov__(r1, r1) ;;-- sets NZP CCs

OS design



Establish Uniform Conventions
Program interface to OS

--- Where are args, return values, return addresses?
  --- Stack usage: push all to stack?
  --- R0 points to data struct, R7 has return address?

--- General abstract device interface:
  --- read, write, append, ...
--- Mode changes, OS module independence
  --- user/supervisor swap, messages to modules

higher-level services

– Clear screen ⇒ { fill display w/ spaces
- how many?
- what's screen size?

– home cursor ⇒ {
- add position counter to putc
- rewrite entire screen, need buffer

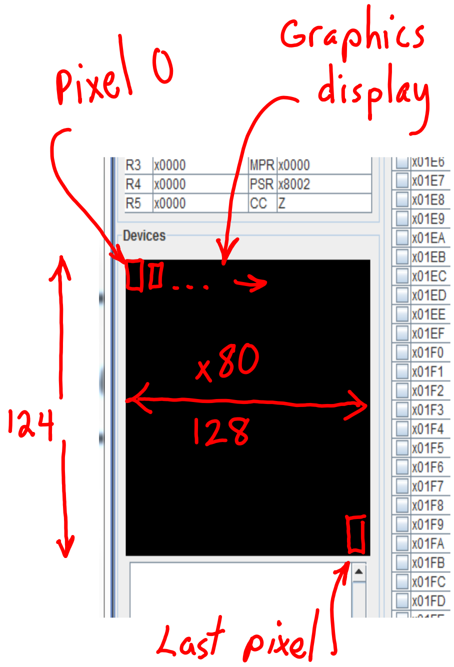
– sub-windows ⇒ {
- define virtual screen objects, hierarchy
- define "current window"

– Processes/owners { – mechanisms for switching, user input

Graphics I/O

16-bit word refers to one pixel,
Each pixel has three intensities R, G, B:

$$0\ \underbrace{R\,R\,R\,R\,R}_{\text{5-bit Red}}\ \underbrace{G\,G\,G\,G\,G}_{\text{5-bit Green}}\ \underbrace{B\,B\,B\,B\,B}_{\text{5-bit Blue}}$$

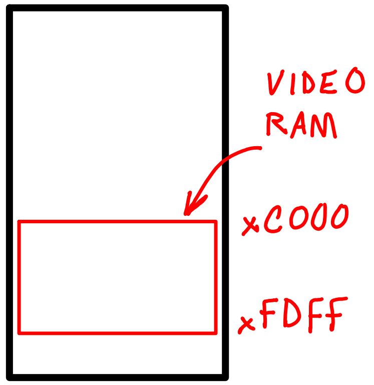


```
R3  x0000      MPR x0000
R4  x0000      PSR x8002
R5  x0000      CC  Z
Devices
```

```
x01E6
x01E7
x01E8
x01E9
x01EA
x01EB
x01EC
x01ED
x01EE
x01EF
x01F0
x01F1
x01F2
x01F3
x01F4
x01F5
x01F6
x01F7
x01F8
x01F9
x01FA
x01FB
x01FC
x01FD
```

PennSim

LC3 Mem



0 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0

7 C

0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0

3 E

0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1

1 F

0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0

0 4 0 0 inc. Red

0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0

0 0 2 0 inc. Green

```
.FILL x7FFF    ;---- White
.FILL x0000     ;---- Black
.FILL x7C00    ;---- Red
.FILL x03E0    ;---- Green
.FILL x001F    ;---- Blue
.FILL x0_0_1_0_0_0_0_1_0_0_0_0_1_0_0_0  ;---- Gray
```

macros?

add R+G → pixe(RØ)

```
LDR R1, GDP, #Red__
LDR R2, GDP, #Green__
ADD R1, R1, R2
STR R1, R0, #0     ;---- R0 points to pixel
```

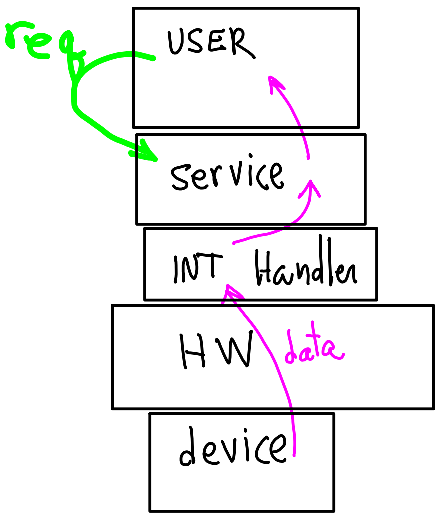
```
.FILL xC000   ;;------ VRAM__
.FILL x0080    ;;------ VRAM_row_inc__

LDR R0, GDP__, #VRAM__
LDR R1, GDP__, #VRAM_row_inc__
LDR R2, GDP__, Green__

;;========== Draw diagonal green line
Loop:

      inc( R0 )                 ;;---- move to next pixel (right)
      ADD R0, R0, R1             ;;---- move down one row
      STR R2, GDP__, #0      ;;---- write green pixel
```

Provide Traps for

- low-level primitives
- high-level ops (e.g. clear)
- objects
  - windows, ...
- pseudo-mouse?
- selection?

Interrupt-driven I/O

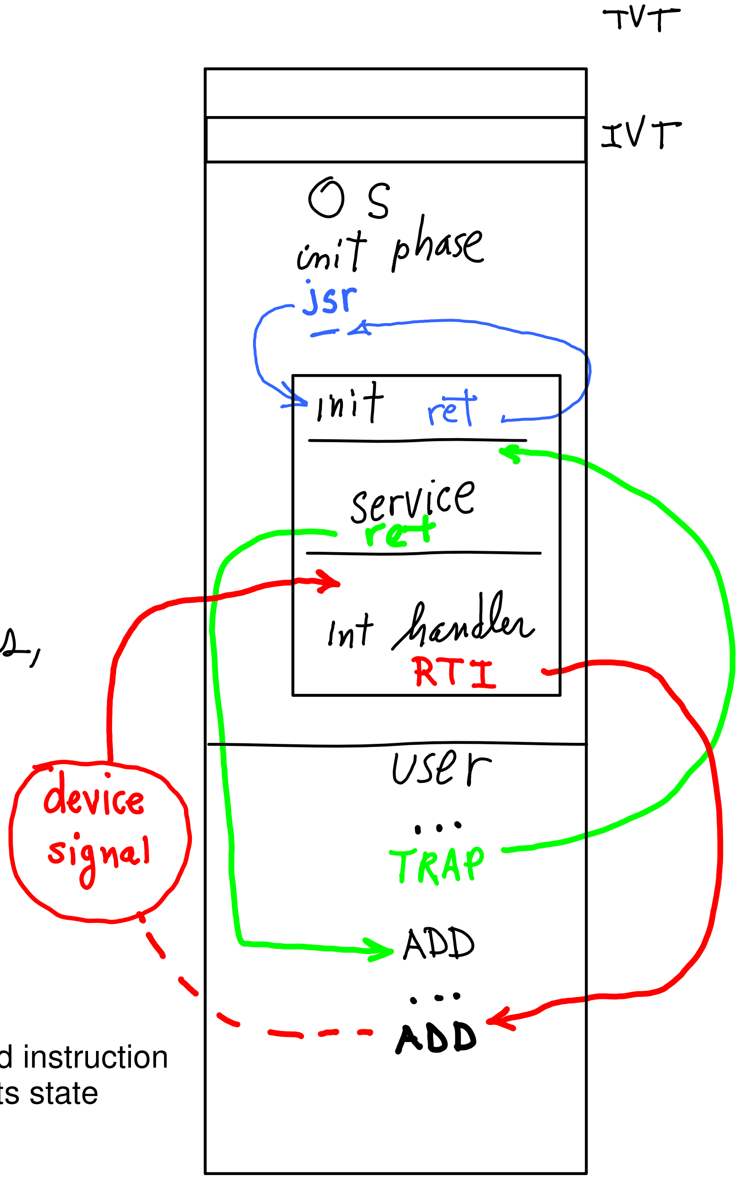
OS layer w/ 3 parts



— user requests.

— service checks status, waits.

— handler delivers, changes status, wakes up service



Interrupts any executing code,
-- might not be requester,
-- another trap or interrupt handler?

Must restart interrupted instruction
-- w/o state changing its state

-- Both handler and user transistion to-from coma state when interrupt occurs.

-- Is either totally or partially aware of state change of other?

-- If state is completely restored, how do handler and service communicate?

Keyboard interrupt handler

In Hardware:

--- save state, turn off interrupts { push(PSR, PC), swap stacks, PSR.Priority = 4
In handler: save regs as needed

--- get data from keyboard, put in buffer

--- handshake kb_ctl: "got data, all done" } In kbctl: a read from KBDR causes KBSR[15] ← 0

--- change status } let world know buffer has data

--- handshake kb_ctl (enable kb interrupts) } kbctl never turns them off (but it should)

--- restore state, turn on interrupts } In handler: restore regs
HW: interrupts turned on via pop(PSR)

--- RTI (pop PC, PSR, swap stacks, change mode)

↑ depends on popped PSR[15]

↑ via pop(PSR)

==========================
Keyboard service
==========================
Forever()

--- check queue for requests ← if none, sleep (jump to OS)

--- check status

--- if status == ready

    copy data to requester
    update buffer
    return from call

--- else

    wait: sleep (jump to OS)

INT handler changes kbsvc's state,
OS restarts kbsvc

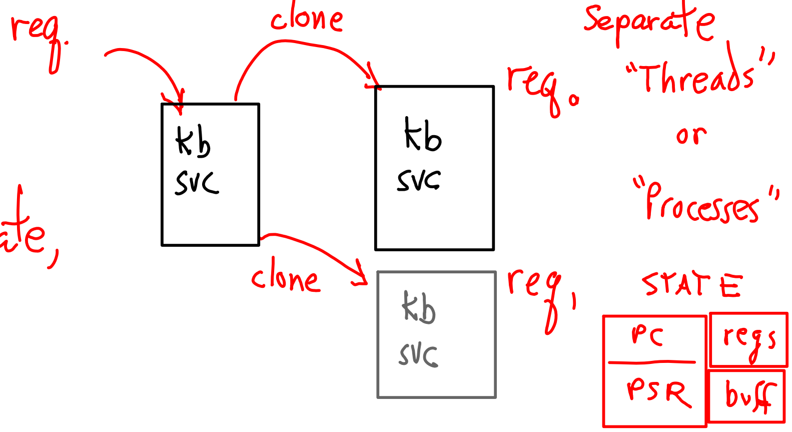
==================
Requester
==================

--- format request
    set number of chars
    set local buffer location

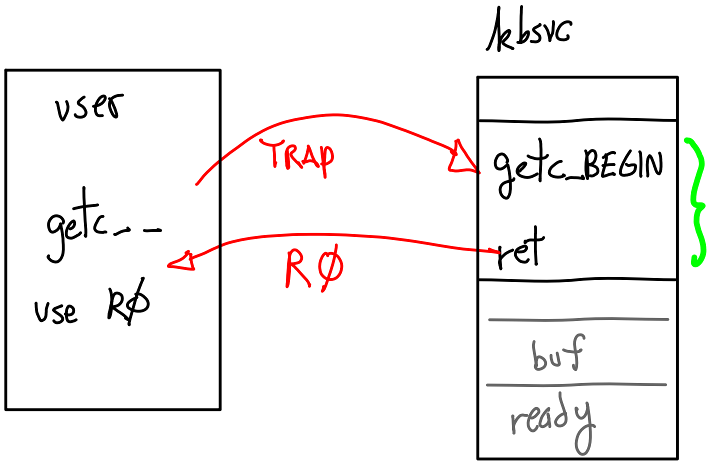
--- send request
    trap to service

--- on return
    use data in local buffer

multiple requestors



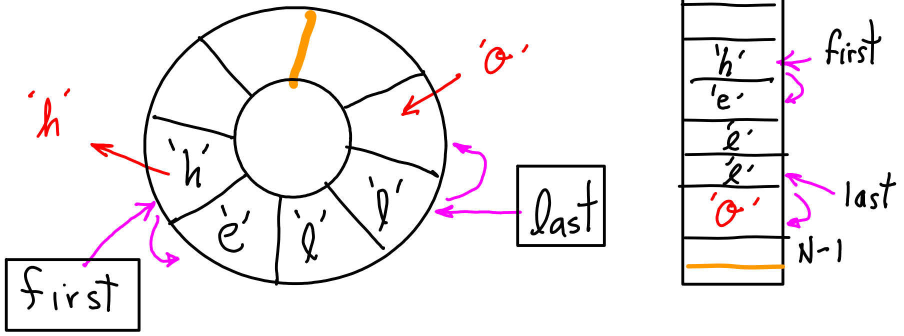
Our svc Req structure



```
ready?
  yes: R0 ← buf
       buf now empty? ready ← 'no'
       ret
  no: wait (sleep?)
```

```
kb_int: buf not full?
          - buf ← char
          - ready ← 'yes'
          - wake_up (requestor)
        else
          ( ignore input?)
```

Circular Buffer



putin: last ++ (%N) ; buf[last] = char

take_out: char = buf[first] ; first ++ (%N)

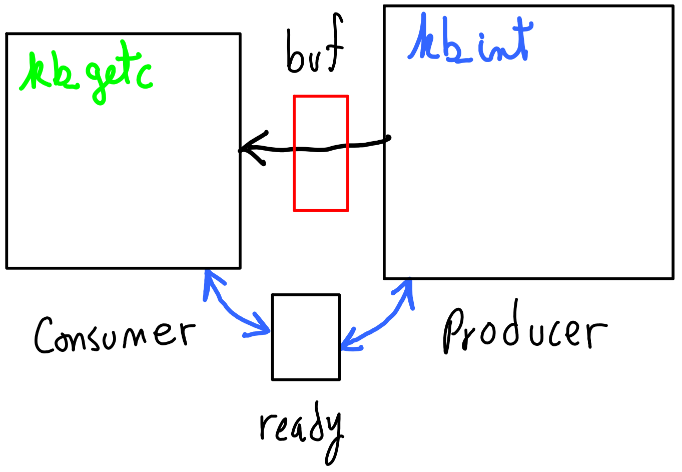
Pointers walk around buffer, inserting at "first", removing at "last"

Buffer Details.
--- What to do when empty?
--- How to avoid overflow?
    if(first == last) ...

Managing shared variables.
int handler, 1 and **trap service, 2**

v: .FILL x0001
1-Reads v , R0 <== 1
(state saved, registers saved, switch)
2-Reads v , R0 <== 1
(state saved, registers saved, switch)
1-Writes v <== R0+1
(state saved, registers saved, switch)
2-Writes v <== R0+1

What's in v? "first"? "last"?



kb_getc and **kb_int** are
cooperating, concurrent,
asynchronous sequential processes:

--- Sharing a resource "buf";
--- Controlling access via "ready";
--- w/ Waiting (sleeping).

Concurrency

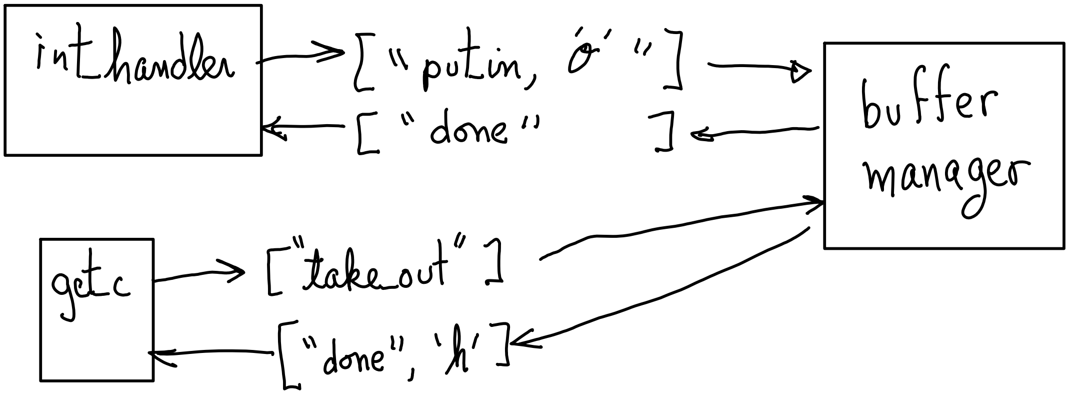
Two general structures

- locks :
  - get sole possession of shared resource
  - other waits until lock released

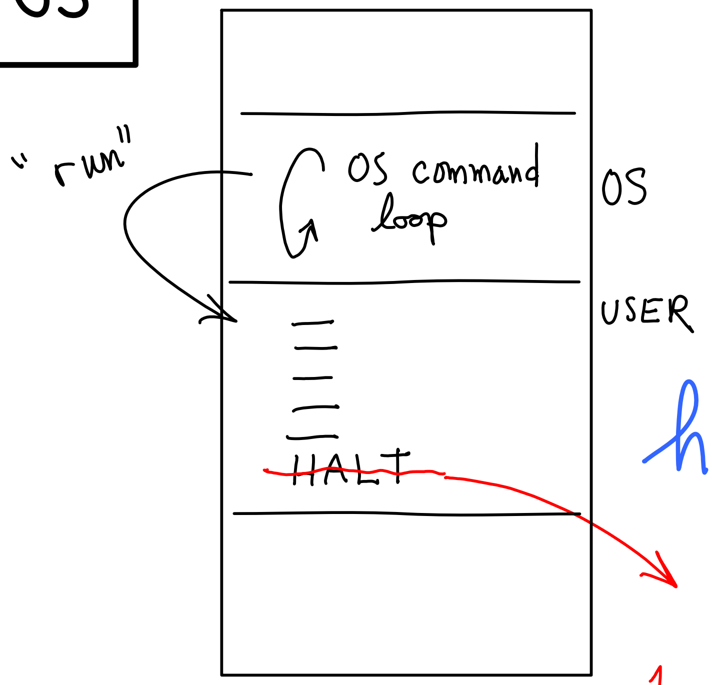
```
getc
    wait( buf_lock)
        char ← take_out()
    unlock(buf_lock)
```

```
int_handler
    wait ( buf_lock)
        put_in( char )
    unlock(buf_lock)
```

- messages:
  - wait for message, send reply
  - send message, wait for reply



Return To OS



What to do when user program finishes?

--- Act like a function exited and return to the place in the OS where the jump occurred?

--- Restart OS at a fixed location?

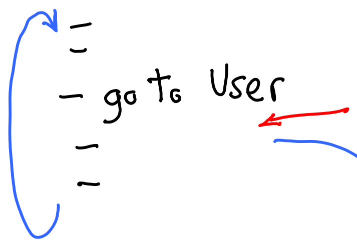
~~halt: turn off sys_clk ?~~ NO!

ret_to_OS

1. How, what mechanism?

2. Where, and do what?

command loop



return, as if subroutine call

Or, never returns, User exits to some OS entry point.

Possibilities

1. – use ret
   - set R7 before jmp to User. Needs user code to remember to save R7. Or push return address, User must pop(R7) then RET. BUT mode change? See (3).

2. – use RTI
   - If super-mode, first need to set up stack w/ dummy PC, PSR
   - If User, will cause privilege exception (Re-enters OS w/ mode change)

3. – return_to_OS__
   - Define a new trap. Trap routine can decide where to jump to in OS. Can also clean up, reinitialize,

     But, can't change mode back to kernel mode?

     Play a trick: use illegal opcode exception to switch modes: set a flag before.

Jump To User Code

Things To do:

- Set return mechanism
- Set arguments, environment vars, etc.
- Set mode to user
- Set up user stack
- jmp to User code

NOTE:

We will only run kernel-mode programs. No need to

--- set user stack
--- change mode

when jumping to a kernel-mode program. But, we will load kernel programs to the user memory area.

Insert a preamble, preamble jumps to main.
User code does RET back to preamble.
Preamble code jumps back to OS.

Switching between code "entities" (concurrent execution)

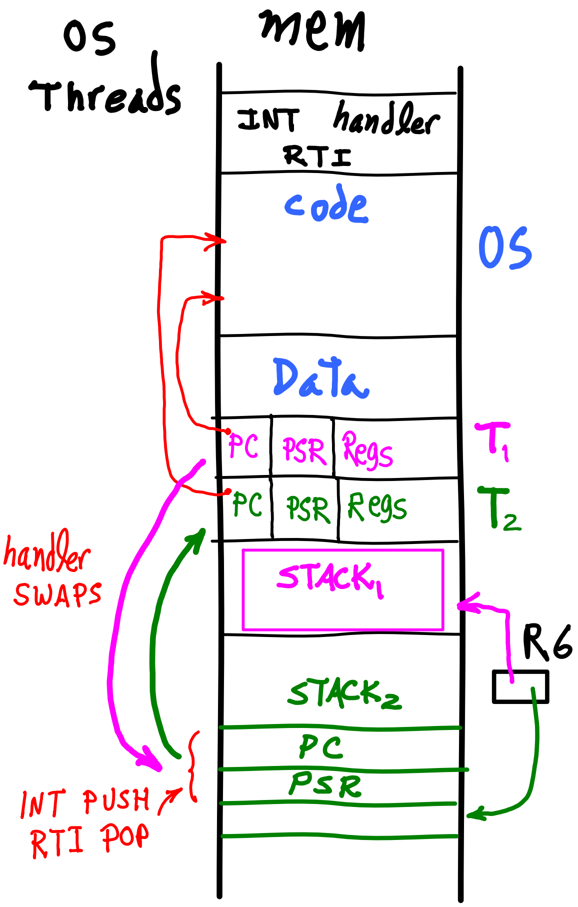
interrupt/exception
--- **saves state** of currently executing code
--- **transfers** execution **to other code**

RTI
--- **restores state**
--- **transfers** execution **back**

Waiting/Sleeping needs same mechanism.

Switch Context
--- Use a hardware (timer) interrupt (involuntary switch)
--- Use illegal opcode (voluntary switch)
interrupt/exception handler does:
--- **save current** code's **state** (**save registers**, stack)
--- **select next context** **(scheduler)**
--- **restore state** of code to switch to (**fill registers**, stack)
--- **push** saved **PSR**
--- **push** saved **PC**
--- **RTI (restores PSR, PC)**

NEED:
--- **List of currently "in" execution entities** (**processes/threads**)
--- for **each item** in list, **a data structure**:
    --- **PSR, PC, R0, R1, ... , R7, (+ why it is waiting)**
--- **Scheduler: select next thread to execute from list**



Linking, Link/Load objects

```
%> cat f.c

#include <stdio.h>
#define MAX_NUMS 10
   ...
int main()
{
  int index;
  int numbers[MAX_NUMS];

  printf("Enter %d numbers.\n", MAX_NUMS);
```

==> f.c uses operating system's services.

==> HALT and OUT.

==> NOT in f.c's C code!

==> **printf**()? IS THAT C TOO?

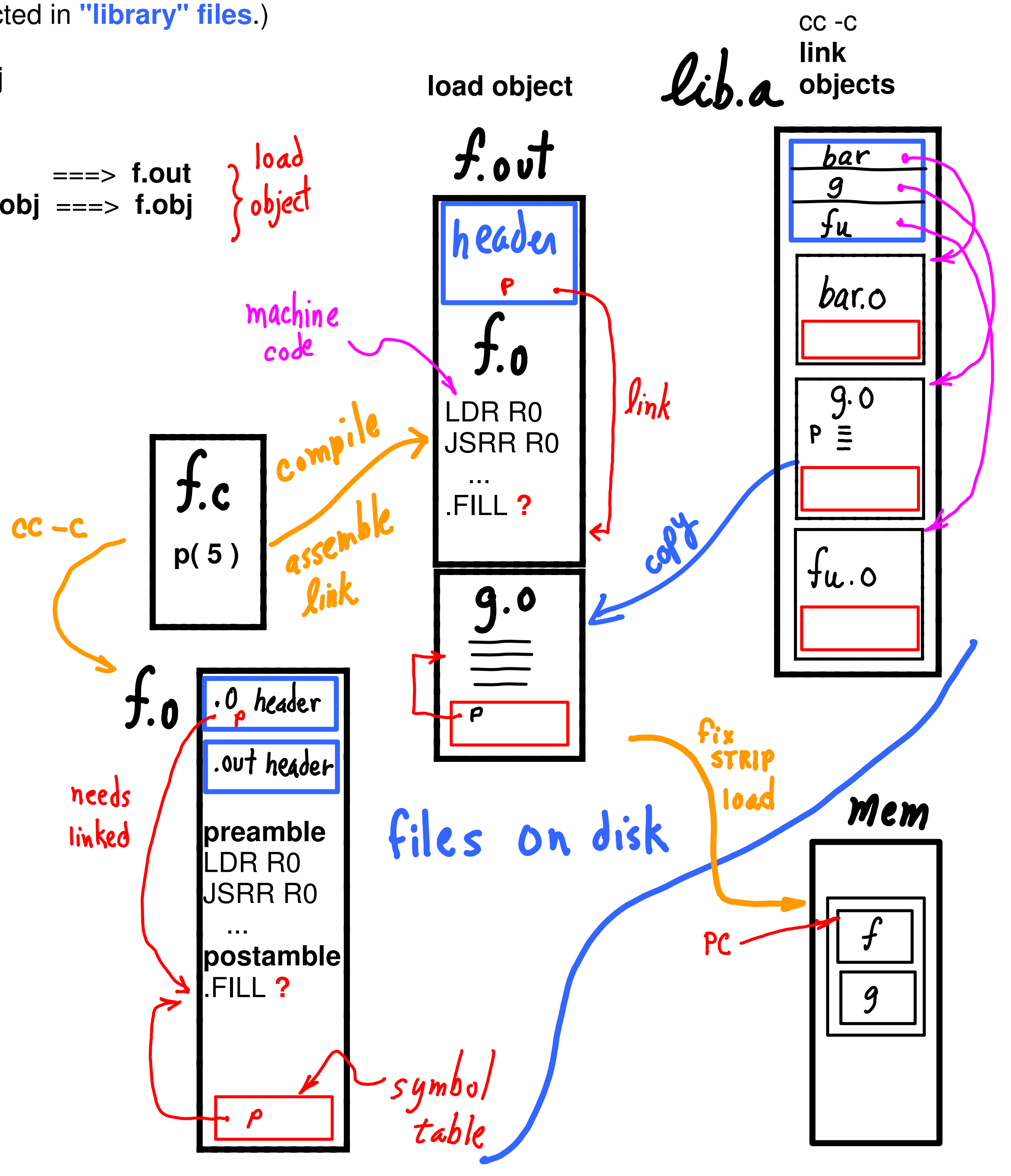
==> **printf.asm** is linked in.

```
cd bin/lcc-1.3/lc3lib/

ls
    getchar.asm     printf.asm
    putchar.asm     scanf.asm
    stdio.asm       stdio.h
```

Usually, **linking not done on .asm files,**
===> link .obj file ("link objects").

Link objects (may be collected in **"library" files**.)
Unix: **cc -c f.c ===> f.o**
LC3: **lcc -c f.c ===> f.obj**

Linking
Unix: **cc f.o g.o bar.o ===> f.out**
LC3: **lcc f.obj g.obj bar.obj ===> f.obj**



Static Linking:

Library header provides **pointers to** sections of **code.**

Sections extracted and **copied to form one file**.

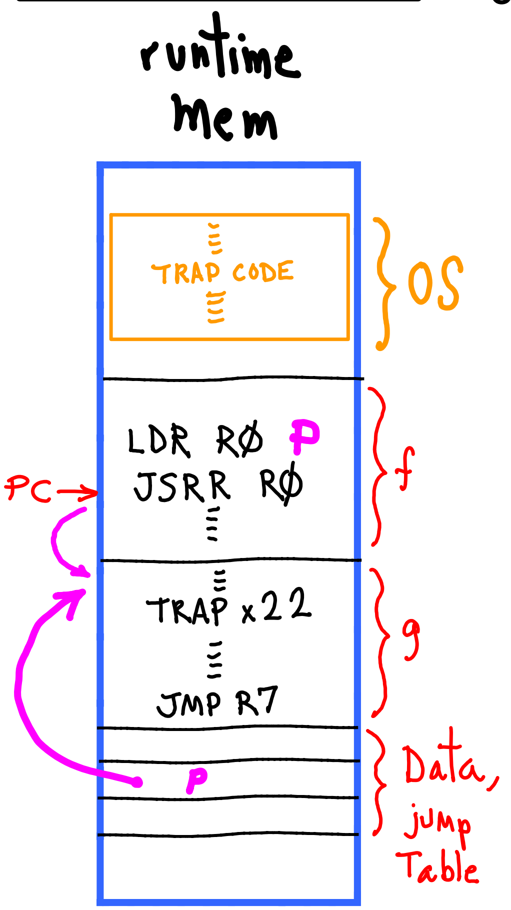
Loader:

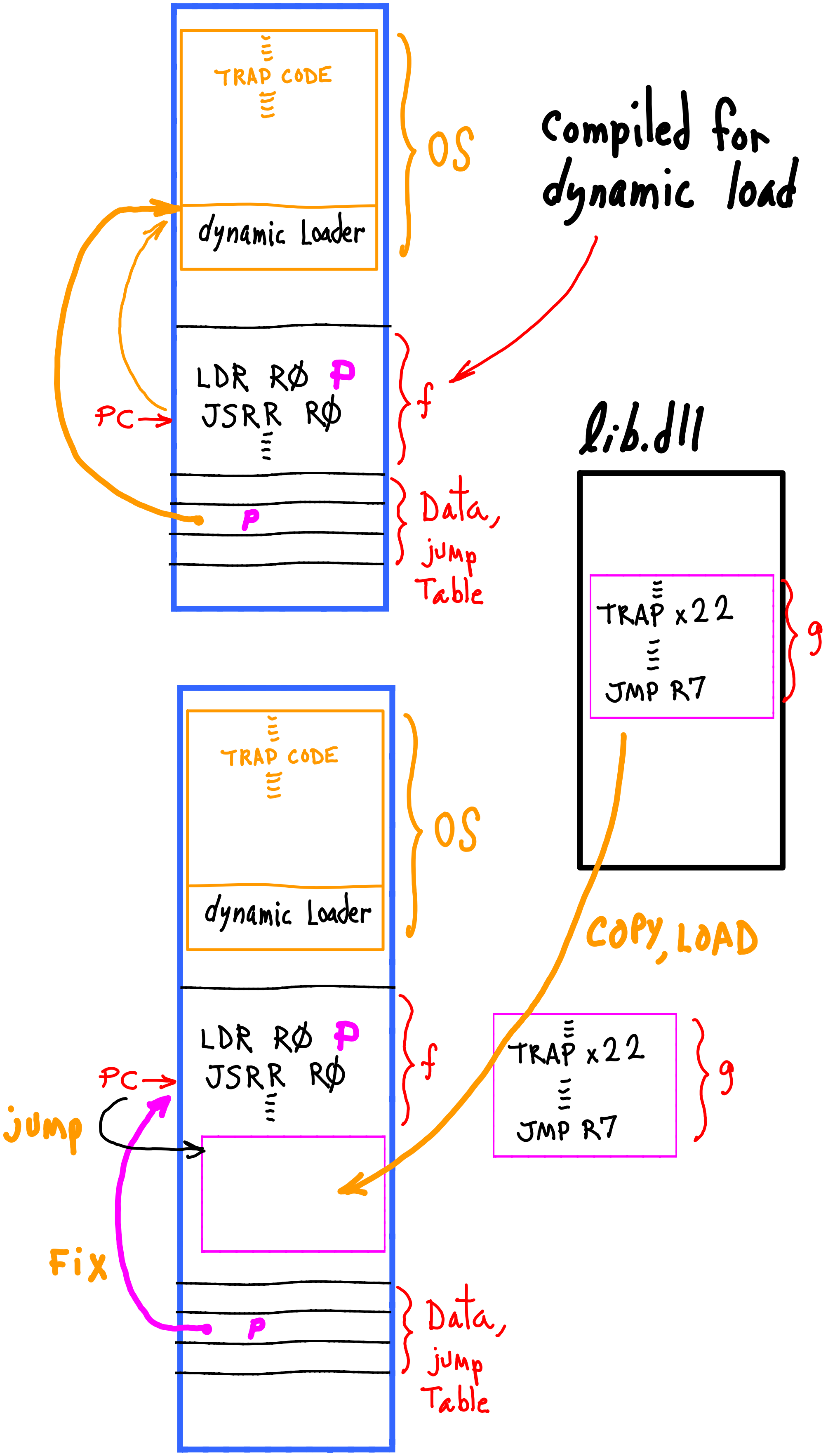
Headers stripped (.out headers), executable **code copied to memory**, along w/ preamble.

References (addresses) **fixed**
---- **at link time**
---- **at load time**

Dynamic Load

How much memory space wasted by g?
What if f never makes jump to p, completely wasted.
Can we do better?





Contrast:

Dynamic linking (.DLL)

--- call is via a jump table

--- jump table filled in as
needed at runtime

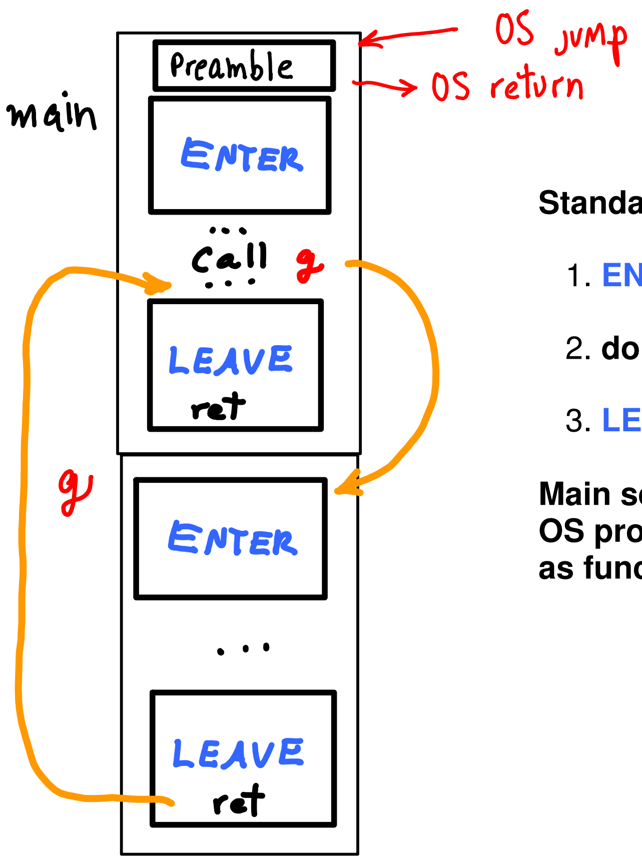
--- 1ST jump goes to loader

--- executable loaded

--- next time, jumps go to
loaded executable, P

--- Pay time for first access
--- after that, same as static.

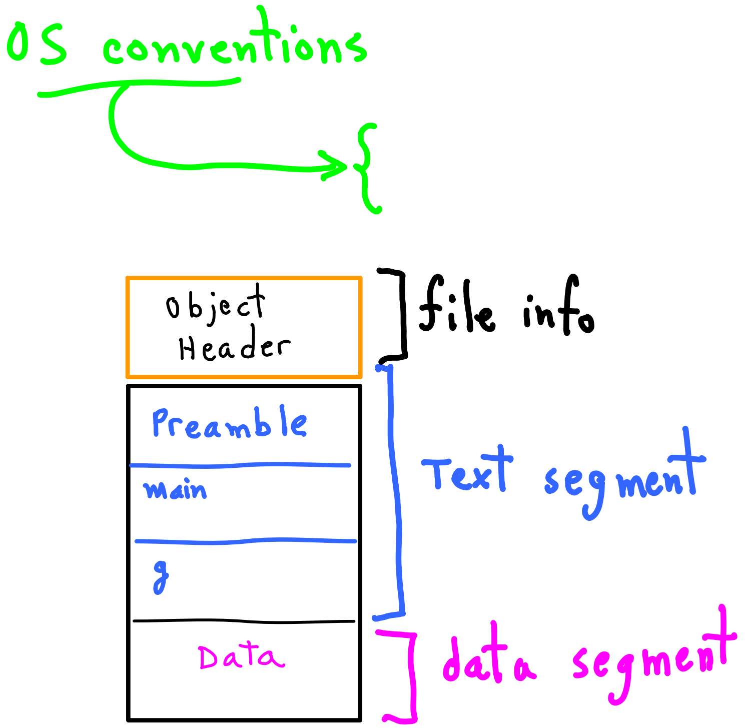
C conventions, lc3 lcc style



Standardized CALL and LEAVE protocol

1. **ENTER: set up stack**
2. **do stuff**
3. **LEAVE: unwind stack**

Main setup just like a function call
OS provides arguments in same way
as function call.



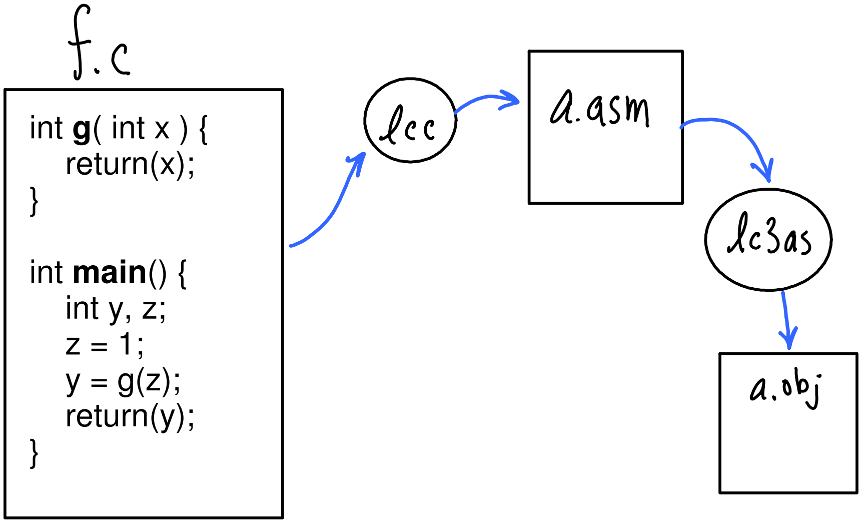
Object structure (.o or .obj)

0. **Header(s)**
   Pointers, offsets, types

1. **Preamble** inserted
   Handles OS conventions

2. **Text Segment**(s)
   machine instructions

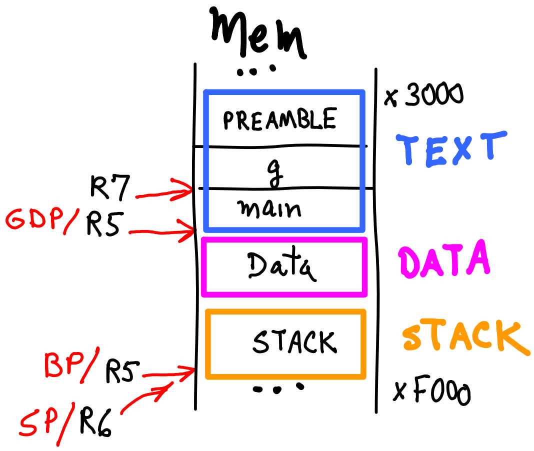
3. **Data Segment**(s)
   pointers to functions
   constants' data
   global variables
   variables' initial values



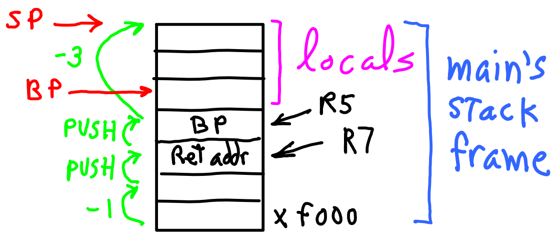
```
int g( int x ) {
   return(x);
}

int main() {
   int y, z;
   z = 1;
   y = g(z);
   return(y);
}
```

```
.Orig x3000
INIT_CODE    ;;----------------- PREAMBLE
LD R6, STACK_POINTER
LD R5, STACK_POINTER
LD R4, GLOBAL_DATA_POINTER
LD R7, GLOBAL_MAIN_POINTER
jsrr R7
HALT
GLOBAL_DATA_POINTER .FILL GLOBAL_DATA_START
GLOBAL_MAIN_POINTER .FILL main ;;-- pointer var.
STACK_POINTER .FILL xF000

;;---------------------------- TEXT SEGMENT
    ...  ( main's and g()'s text)  ...

;;---------------------------- DATA SEGMENT
GLOBAL_DATA_START:
g    .FILL lc3_g  ;;-- Pointer variable to g()
L1_f .FILL lc3_L1_f
L4_f .FILL lc3_L4_f
L3_f .FILL #2      ;;-- CONST 2
L5_f .FILL #1      ;;-- CONST 1
L2_f .FILL #5      ;;-- CONST 5
.END
```

```
int g( int x, int w ) {
     int y, z;
     y = x+5+w;
     z = y+2;
     return(z);
}

int main(void){
     int a, b, c;
     a = 1;
     b = 2;
     c = a+b;
     return( g(b, c) );
}
```

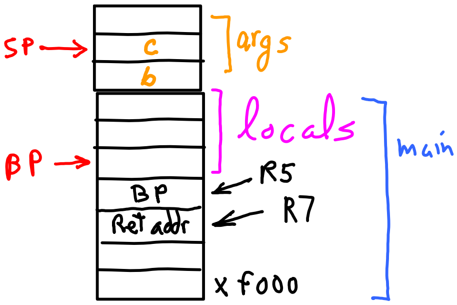


```
main
     ;;-------- BEGIN ENTER ---------
ADD R6, R6, #-1   ;;-- allocate ret val space
ADD R6, R6, #-1   ;;-- SP--
STR R7, R6, #0    ;;-- push ret addr
ADD R6, R6, #-1   ;;-- SP--
STR R5, R6, #0    ;;-- push BP
ADD R5, R6, #-1   ;;-- set new BP
                  ;;------ allocate locals
ADD R6, R6, #-3
     ;;-------- END ENTER -----------
```



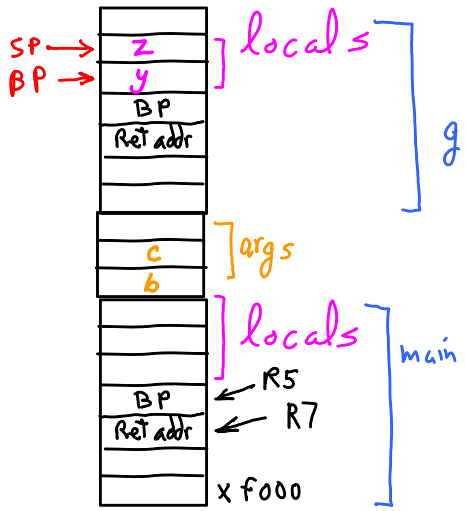
```
ldr R7, R5, #0   ;-- R7 <== b
ldr R3, R5, #-1  ;-- R3 <== a
add R3, R3, R7   ;-- R3 <== a+b
str R3, R5, #-2  ;-- c   <== R3
ldr R3, R5, #-2  ;--
ADD R6, R6, #-1  ;-- sp--
STR R3, R6, #0   ;-- push c
ADD R6, R6, #-1  ;-- sp--
STR R7, R6, #0   ;-- push b
ADD R0, R4, #0   ;-- R0 <== address of g() pointer
LDR R0, R0, #0   ;-- R0 <== address of g()
jsrr R0          ;-- call g()
```

} do arithmetic

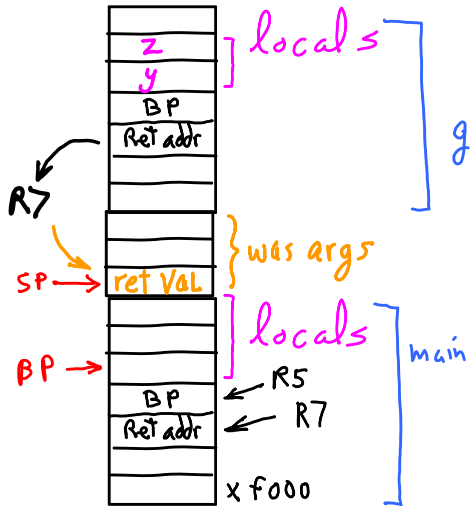


On call, SP points to 1st arg

```
lc3_g
    ;;-------- BEGIN ENTER ---------
ADD R6, R6, #-1  ;;-- allocate ret val space
ADD R6, R6, #-1  ;;-- SP--
STR R7, R6, #0   ;;-- push ret addr
ADD R6, R6, #-1  ;;-- SP--
STR R5, R6, #0   ;;-- push BP
ADD R5, R6, #-1  ;;-- set new BP
                 ;;----- allocate locals
ADD R6, R6, #-2
    ;;-------- END ENTER -----------
```

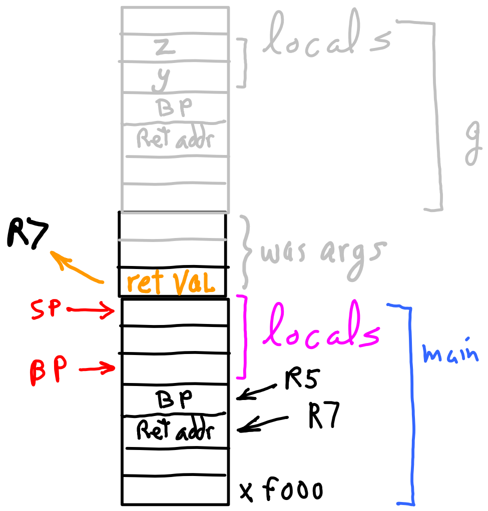


```
    ;;-------- BEGIN-LEAVE ---------
LDR R6, R5, #5   ;;-- SP to last arg
STR R7, R6, #0   ;;-- ret val to last arg
LDR R7, R5, #2   ;;-- get saved ret addr
LDR R5, R5, #1   ;;-- restore BP
    ;;-------- END-LEAVE ---------
RET
```



```
LDR R7, R6, #0     ;-- pop ret val to R7
ADD R6, R6, #1     ;-- SP++
```

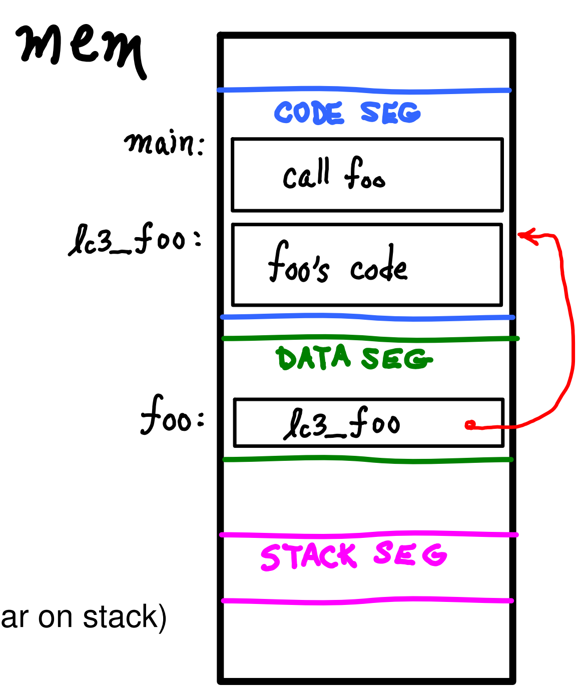
On return, pop result
(or pop void result)



What is a function's name?

It's a pointer variable (a location in memory) (that stores an address)

void foo (void) {...}



You can pass it as an argument

do_something (foo);

pass by value? (value on stack)

pass by reference? (address of var on stack)

How do we use it? An argument Variable declaration:

void do_something (void (* foo) (void)) { ... }

a formal parameter, a variable

That can be de-referenced, it's value is an address

and that value used as a function address to jump to.

Now we can make the call:

(*foo)( );

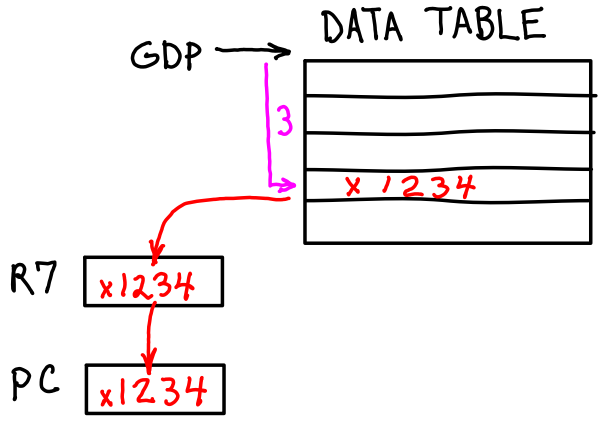
For the compiler, the name is an offset into the DATA segment. The call uses it:

compile time

Symbol Table

foo	3

runtime



```
LDR R7, GDP__, #3
JSRR R7
```

← get the pointer value

← use its value: derefence

Here's a .o file produced by gcc.

You won't find printf here, it hasn't been linked yet.

Assembly is in ATT syntax: destination on right.

You can guess at meaning.

```
%> gcc -S fo.c
%> more f.s

        .file   "f.c"
        .def    ___main;     .scl    2;      .type   32;
        .endef
        .section .rdata,"dr"
LC0:
        .ascii "Enter %d numbers.\12\0"

        .text
.globl _main
        .def    _main;       .scl    2;      .type   32;
        .endef
_main:
        pushl  %ebp
        movl   %esp, %ebp
        subl   $104, %esp
        andl   $-16, %esp
        movl   $0, %eax
```

ASCII x0A = LF

ASCII x00 = NUL

— save BP : push BP

— new BP : SP → BP

— make space : SP - 104

— align: x0 → SP[3:0]

• • • — more preamble