

EE445M/EE380L.12

Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 2: Software Development, Design, Implementation, Debugging

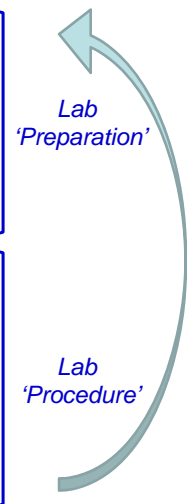
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Development Process

1. Analyze (Ask)
 - Requirements, specifications
2. Design (Think)
 - Dataflow/call graphs, flowcharts, OO
3. Implement (Do)
 - Code, coding styles, documentation
4. Debug and test (Check)
 - Verification (correctness)
 - Validation (performance)



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Development Tools

- Editor
- Version/Revision Control
- (Cross-)Compiler
- Simulator
- Debugger
- Integrated Development Environment (IDE)

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Announcements

- Labs
 - Week of 1/27: TA demos, partnering & boards
 - Week of 2/3: Lab 1 Prep
 - Week of 2/10: Lab 1 Demo/Report, Lab 2 Prep
- Lab submissions
 - Preparation: software design (oral)
 - Demo: software implementation (Github)
 - Submission and repository info will be mailed
 - Report: software documentation (Canvas)

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Modular Programming

- Encapsulation (private)
 - Information hiding
 - Reduce coupling
- Abstraction (public)
 - Well-defined external interfaces
 - Separate mechanism from policy

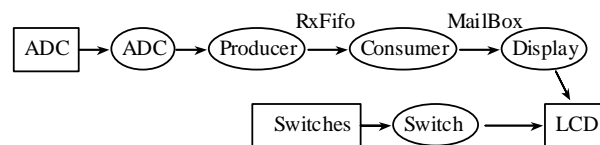
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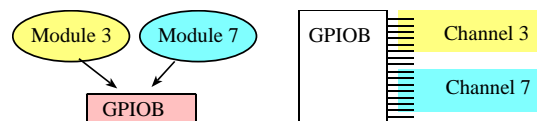
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Dataflow & Call Graphs

- Dataflow graphs
 - Parallel or sequential execution



- Call graphs
 - Use to identify potential conflicts



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Modular Programming in C

- Naming conventions
 - Object name has *Module Name* and underline
 - E.g. `UART_xxx`
- Public object declarations in header file
 - Avoid public global variables
 - Otherwise declared as `extern`
- Private objects & definitions in C file
 - Private globals have `static` modifier
 - Public globals locally defined w/o `extern`

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Object-Oriented Programming (OOP)

- Elevate modules into first-class citizens
 - Encapsulation of data & code
 - Member variables and functions (*methods*)
 - Dynamic vs. static scope & lifetime
 - Blueprint (*class*) and instances (*objects*)
 - Initialization & tear-down (*constructor/destructor*)
 - Plus inheritance, polymorphism, ...
 - Further increase opportunities for reuse

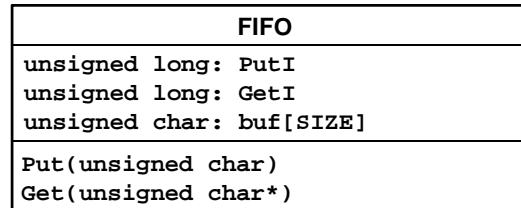
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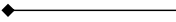
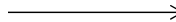
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Class Diagrams (UML)

- Classes & objects



- Relationships

- Membership (“has a”) 
- Inheritance (“is a”) 

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Objects in C

- “Class” declaration (header file)

```
#define AddFifo(NAME,SIZE,TYPE, SUCCESS,FAIL) \
unsigned long volatile PutI ## NAME; \
unsigned long volatile GetI ## NAME; \
TYPE static Fifo ## NAME [SIZE]; \
void NAME ## Fifo_Init(void){ \
    PutI ## NAME= GetI ## NAME = 0; \
} \
int NAME ## Fifo_Put (TYPE data){ \
    if(( PutI ## NAME - GetI ## NAME ) & ~(SIZE-1)){ \
        return(FAIL); \
    } \
    Fifo ## NAME[ PutI ## NAME &(SIZE-1)] = data; \
    PutI ## NAME ## ++; \
    return(SUCCESS); \
} \
int NAME ## Fifo_Get (TYPE *datapt){ \
    if( PutI ## NAME == GetI ## NAME ){ \
        return(FAIL); \
    } \
    *datapt = Fifo ## NAME[ GetI ## NAME &(SIZE-1)]; \
    GetI ## NAME ## ++; \
    return(SUCCESS); \
}
```

“Member” variables

“Methods”

- Object instantiation

```
AddFifo(Tx,32,unsigned char, 1,0)
```

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Structured Programming

- Flowcharts

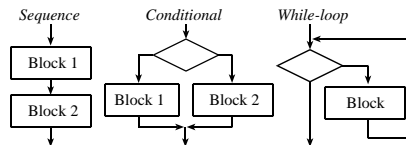


Figure 2.1. Flowchart showing the basic building blocks of structured programming.

- Parallel constructs

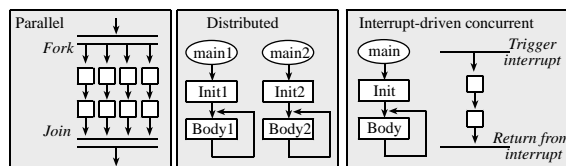


Figure 2.2. Flowchart symbols to describe parallel, distributed, and concurrent programming.

Design Patterns

- Buffered I/O

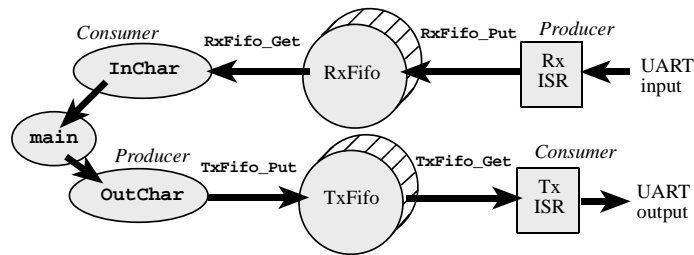
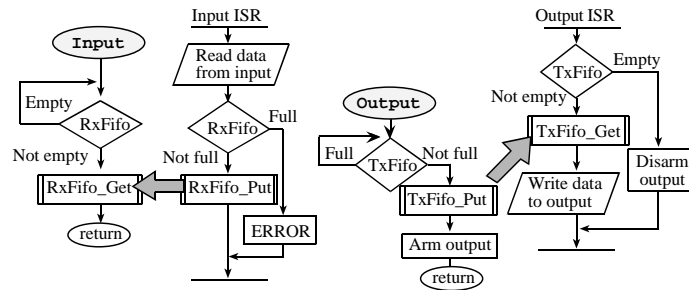


Figure 3.3. A data flow graph showing two FIFOs that buffer data between producers and consumers.

[UARTInts_4C123.zip](#)

Buffered I/O

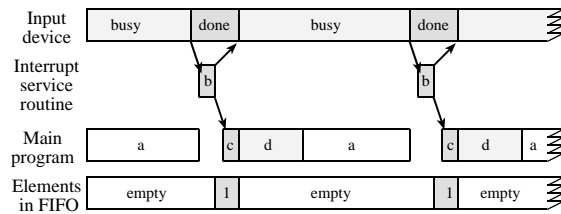
- Using interrupt-driven I/O synchronization



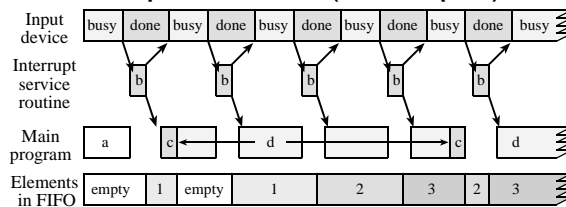
UARTInts_4C123.zip

Input Synchronization

- I/O bound input device (slow input)

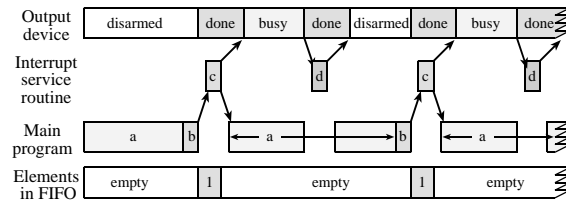


- CPU bound input device (fast input)

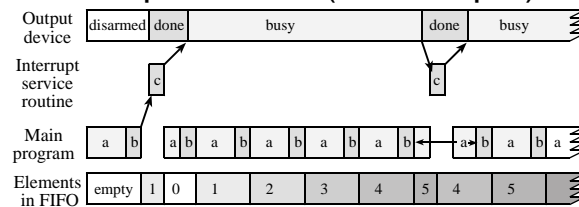


Output Synchronization

- CPU bound output device (fast output)



- I/O bound output device (slow output)



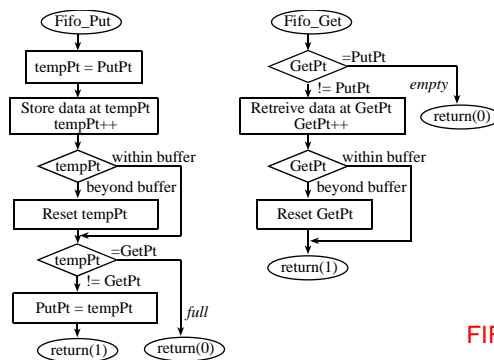
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FIFO Implementation

- Pointer- or index-based implementation



FIFO_4C123.zip

Figure 3.19. Flowcharts of the pointer implementation of the FIFO queue.

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Coding Style

- Find your own conventions
 - Naming
 - Meaning, type of variables & functions
 - Readability
 - Indentation, white space
 - Documentation
 - Comments for every module, function, code block

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Testing

- Unit vs. integration testing
 - Test function, module before integrating into next bigger system
- Black box vs. white box testing
 - Just inputs/outputs vs. can probe inside
 - Know what it does vs. know how it works
 - Have interfaces vs. have internals

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Debugging

1. Stabilize the system (reproducibility)
 - Creating a test routine that fixes (or stabilizes) all inputs
 - Can reproduce the exact inputs over and over again
 - Modify the program
 - Change in outputs is a function of modification and not due to a change in the input parameters

2. Debugging instruments (control, observability)
 - Code that is added to isolate origin of bug
 - “Rough and ready” manual methods
 - Desk-checking, dumps, printf statements
 - Intrusive vs. non-intrusive
 - Measure of the degree of perturbation caused in program behavior by an instrument

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Debugging Tools (1)

- Software debuggers
 - Breakpoints
 - Replacing the instruction with a trap
 - Can not be performed when the software is in ROM
 - Single step
 - Implicit breakpoints or periodic interrupts
 - Inspection
 - Processor state (registers), memory

- Hardware debuggers (local or remote via JTAG)
 - Interface with microcomputer chip itself
 - Communicates with the debugging computer
 - Ability to observe software execution in real time
 - Set breakpoints, single step
 - Ability to stop the computer and set hardware breakpoints
 - Processor, memory and I/O ports are accessible while running
 - Hardware support to break on events (e.g. memory access)

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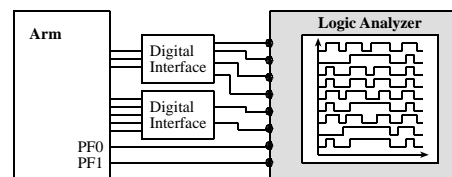
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Debugging Tools (2)

- Logic analyzer
 - Multiple channel digital storage scope
 - Numerous digital signals at various points in time
 - triggering to capture data at appropriate times
 - Good for real time observation of I/O signals
 - Attached to strategic I/O signals, real-time measurement
 - Attached to heart beats, profile execution
 - Massive amount of information
 - must interpret the data
 - Nonintrusive

- PC-based

<http://www.digilentinc.com/analogdiscovery/>
 Software: <http://www.digilentinc.com/waveforms/>
<http://www.usbee.com>
<http://www.saleae.com>



A logic analyzer and example output.

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Functional Debugging

- Verification of input/output parameters
 - What data is processed at specific points
- A static process where
 - inputs are supplied,
 - the system is run, and
 - the outputs are compared against expected results.

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Functional Debugging Methods

- Intrusive methods
 - Single stepping or trace
 - Breakpoints
 - Instrumentation w/ print statements
 - Difficult in embedded systems
 - A standard output device may not be available
 - Output may be slow (relative to rest of system)
 - Output device used for normal operation
 - Send print output to special debug device
 - E.g. UART, see Lecture 1

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Debugging Instruments (1)

- Dump into array without filtering
 - Dumps strategic information into an array at run time
 - Observe the contents of the array at a later time
 - Use debugger to visualize when running

```
long DebugList[100];
unsigned int DebugCnt=0;
void RecordIt(long data){
    if(DebugCnt==100)return;
    DebugList[DebugCnt]=data;
    DebugCnt++;
}
```

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Debugging Instruments (2)

- Dump into array with filtering
 - A software/hardware condition that must be true in order to place data into the array

```

if(condition){
    RecordIt(MyData);
}

```

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Debugging Instruments (3)

- Monitor using output port
 - A monitor is an independent output process
 - executes very fast, so is minimally intrusive
 - small amounts of strategic information (enter/exit block)
 - Examples
 - LCD display
 - LED's on individual otherwise unused output bits

```

#define PF1                (*(volatile unsigned long *)0x40025008)
#define GPIO_PORTF_DATA_R (*(volatile unsigned long *)0x400253FC)
PF1 = 0x02; // atomic (specific for TM4C)
GPIO_PORTF_DATA_R |= 0x02; // not atomic
PF1 = 0x00; // atomic (specific for TM4C)
GPIO_PORTF_DATA_R &= ~0x02; // not atomic

```

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Debugging Instruments (2)

- Monitor using output port
 - Measure using scope or logic analyzer
 - Again, atomicity in parallel/interrupt cases

4804	LDR r0,[pc,#16]	;r0= 0x400063FC	GPIO_PORTC_DATA_R = 0x20;
5800	LDR r0,[r0,#0x00]	;r0=PORTC	
F0400020	ORR r0,r0,#0x20	;set bit 5	
4903	LDR r1,[pc,#12]	;r1= 0x40006000	
F8C103FC	STR r0,[r1,#0x3FC]	;write PORTC	
4804	LDR r0,[pc,#16]	;r0= 0x400063FC	GPIO_PORTC_DATA_R = 0x40;
5800	LDR r0,[r0,#0x00]	;r0=PORTC	
F0400040	ORR r0,r0,#0x40	;set bit 6	
4903	LDR r1,[pc,#12]	;r1= 0x40006000	
F8C103FC	STR r0,[r1,#0x3FC]	;write PORTC	

These subroutine have critical sections because of the read-modify-write access to a shared global.

2020	MOVS r0,#0x20		GPIO_PORTC5 = 0x20;
4902	LDR r1,[pc,#8]	;r1=0x40006080	
6008	STR r0,[r1,#0x00]	;set bit 5	
2020	MOVS r0,#0x40		GPIO_PORTC6 = 0x40;
4902	LDR r1,[pc,#12]	;r1=0x40006100	
6008	STR r0,[r1,#0x00]	;set bit 6	

These subroutines do not have critical sections because the write access is atomic (bit-specific addressing).

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Performance Debugging

- Verification of timing behavior of system
 - When do specific events occur
 - Measure dynamic efficiency of software
 - Delta time spent in pieces of code
- A dynamic process
 - System is run, and
 - dynamic behavior compared to expected results

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Performance Analysis

- Count processor cycles
 - Very hard in modern processors
 - Many dynamic run-time effects
 - Pipeline, caches, branch predictors, out-of-order
 - See ARM Technical Reference Manual
https://static.docs.arm.com/ddi0439/b/DDI0439B_cortex_m4_r0p0_trm.pdf (Table 3.1)
 - Need empirical measurements

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Performance Instruments (1)

- Independent counter
 - Use internal SysTick timer

```

unsigned long before, elapsed;
// ranges from 0 to NVIC_ST_RELOAD_R
unsigned long OS_Time(void) {
    return NVIC_ST_CURRENT_R; // 20ns
}
void main(void) {
    before = OS_Time(); // initialize
    // software to test, assume no interrupts
    ...
    elapsed = OS_TimeDiff(OS_Time(), before);
}

```

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Performance Instruments (2)

- Dump with independent counter

```

unsigned long Tbuf[100];
unsigned int Tcnt=0;
void RecordTime(void){
    if(Tcnt==100) // Buffer full?
        return;
    Tbuf[Tcnt] = NVIC_ST_CURRENT_R;
    // 24-bit SysTick counter, 20ns
    Tcnt++;
}

```

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Performance Instruments (3)

- Monitor using output port
 - Measure using scope or logic analyzer
 - Again, atomicity in parallel/interrupt cases
 - What about overhead?

```

void main(void){
    ss = 100;
    while(1){
        GPIO_PORTD_DATA_R |= 0x20;
        tt = sqrt(ss);
        GPIO_PORTD_DATA_R &= ~0x20;
    }
}

```

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Profiling

- Collect the time history of strategic variables
 - Where executing, and when it is executing
 - What is the data, and when is the data these values
- Where executing, when it is executing, and what is the data

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Profiling Instruments (1)

- Dump into an array

```

unsigned long time[100]; // when
unsigned short place[100]; // where
unsigned short data[100]; // what
unsigned short n = 0;
void profile(unsigned short thePlace, unsigned short theData) {
    if(n==100) return;
    time[n] = OS_Time(); // current time
    place[n]= thePlace;
    data[n] = theData;
    n++;
}
unsigned short sqrt(unsigned short s) {
    unsigned short t,oldt;
    t=0; // secant method
    profile(0,t);
    if(s>0) {
        profile(1,t);
        t=32; // initial guess 2.0
        do{
            profile(2,t);
            oldt=t; // from the last
            t=((t*t+16*s)/t)/2;}
        while(t!=oldt);}
    profile(3,t);
    return t;
}

```

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Profiling Instruments (2)

- Profile using an output port
 - Output 1,2,3,... or 1,2,4,... (better)

```

unsigned int sqrt(unsigned int s){
    unsigned int t,oldt;
    GPIO_PORTC4 = 0x10;
    t=0; // secant method
    if(s>0) {
        GPIO_PORTC5 = 0x20;
        t=32; // initial guess 2.0
        do{
            GPIO_PORTC6 = 0x40;
            oldt=t; // from the last
            t=((t*t+16*s)/t)/2;
            GPIO_PORTC6 = 0;
        }
        while(t!=oldt);
        GPIO_PORTC5 = 0;
    }
    GPIO_PORTC4 = 0;
    return t;
}

```

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Profiling Instruments (3)

- Thread profiling using output port
 - When is which thread running?
 - Set bit on enter, clear bit on exit

```

GPIO_PORTC4 = 0x10; // Thread 1
RxFifo_Put(data);
GPIO_PORTC4 = 0;

```

```

GPIO_PORTC5 = 0x20; // Thread 2
TxFifo_Get(&data);
GPIO_PORTC5 = 0;

```

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CPU Bound or I/O Bound?

- Measure FIFO size versus time
 - When is it I/O bound? When is it CPU bound?

```
unsigned short TxFifo_Size(void){
    if(TxPutPt<TxGetPt){
        return(TxPutPt+TXFIFOSIZE-TxGetPt);
    }
    else{
        return(TxPutPt-TxGetPt);
    }
}
```

- Collect a histogram of FIFO sizes

```
unsigned long histogram[TXFIFOSIZE];
void Collect(void){
    histogram[TxFifo_Size()]++;
}
```

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Debugging Real-Time Systems

- Events that are observable in real time
 - The input and output signals of the system
 - Observe using logic analyzer
 - Dumps
 - Record in real time, observe later off line
 - Extra output pins
 - Heart beats, monitors, profiling (logic analyzer)

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Debugging Style

- Develop your own unique style
 - Place all print statements in a unique column
 - Specific pattern in their names
 - Test a run time global flag
 - Leaves a copy of the code in the final system
 - Simplifies “on-site” customer support
 - Use conditional compilation (`#ifdef DEBUG`)
 - Performance and effectiveness
 - For safety-critical systems leave instruments in