EE445M/ECE380L.12
Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 2: Software Development, Design, Implementation, Debugging

Announcements

- Labs
  - Week of 1/24: TA demos, partnering & boards
  - Week of 1/31: Lab 1 Prep
  - Week of 2/7: Lab 1 Demo/Report, Lab 2 Prep
- Lab submissions
  - Preparation: software design (oral/paper)
  - Demo: software implementation (Github)
    - Submission and repository info will be mailed
  - Report: software documentation (Canvas)

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)

Lab 'Preparation' (steps 1–2)

Lab 'Procedure' (steps 3–4)

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 3

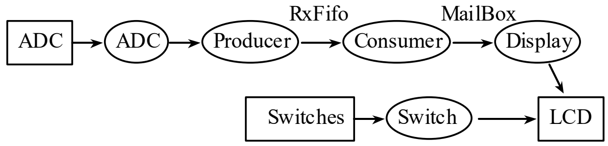
Development Tools

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

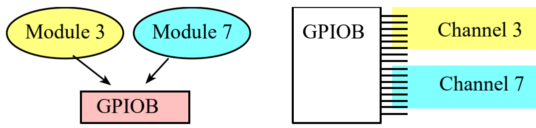
Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 4

Software Design

- Dataflow graphs
  - Parallel or sequential execution



- Call graphs
  - Use to identify potential conflicts



Modular Programming

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

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`**

Object-Oriented Programming (OOP)

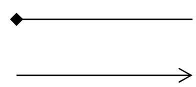
- Elevate modules into first-class citizens
  - Encapsulation of data & code
    - Member variables and functions (*methods*)
  - Dynamic vs. static scope & lifetime
    - Blueprint (*class*) and instances (*objects*)
    - Initialization & tear-down (*constructor/destructor)*
  - Plus inheritance, polymorphism,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

Class Diagrams (UML)

- Classes & objects

FIFO
unsigned long: PutI unsigned long: GetI unsigned char: buf[SIZE]
Put(unsigned char) Get(unsigned char*)

- Relationships
  - Membership ("has a")
  - Inheritance ("is a")



Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 9

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)
```

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 10

Design Patterns

- Buffered I/O

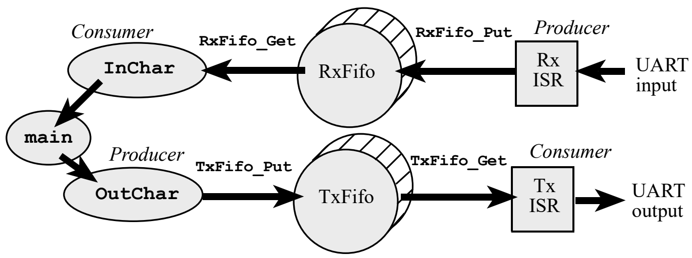


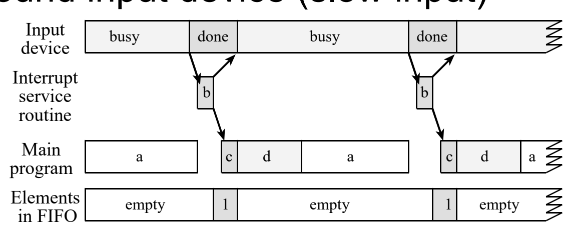
Figure 3.3. A data flow graph showing two FIFOs that buffer data between producers and consumers.

UARTInts_4C123.zip

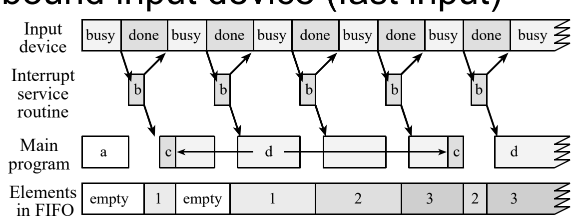
Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 11

Input Synchronization

- I/O bound input device (slow input)



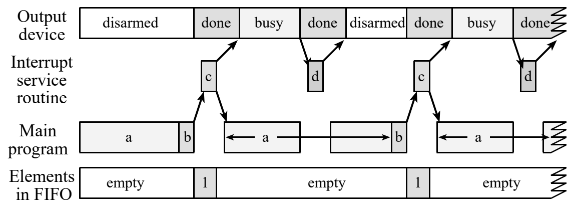
- CPU bound input device (fast input)



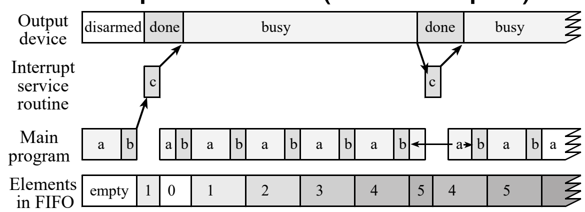
Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 12

Output Synchronization

- CPU bound output device (fast output)



- I/O bound output device (slow output)



Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 13

Structured Programming

- Flowcharts

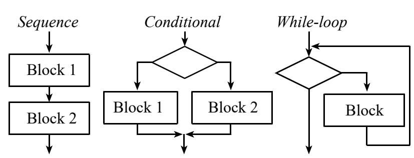


Figure 2.1. Flowchart showing the basic building blocks of structured programming.

- Parallel constructs

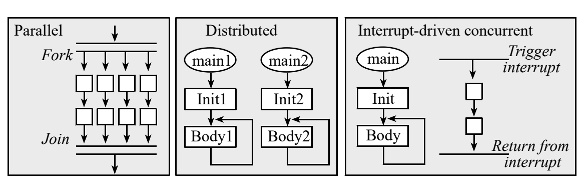
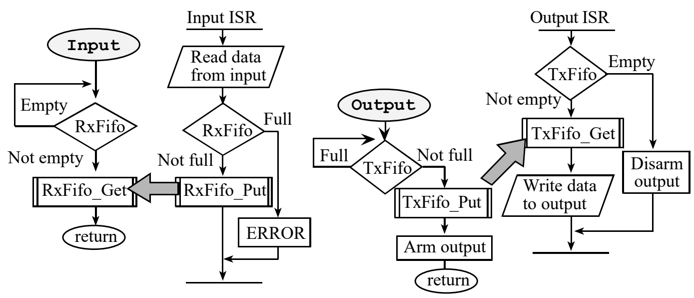


Figure 2.2. Flowchart symbols to describe parallel, distributed, and concurrent programming.

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 14

Buffered I/O

- Using interrupt-driven I/O synchronization

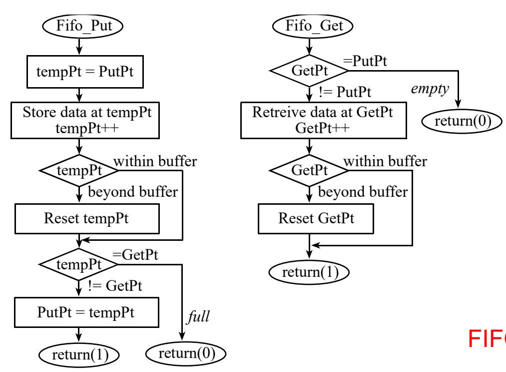


UARTInts_4C123.zip

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 15

FIFO Implementation

- Pointer- or index-based implementation



FIFO_4C123.zip

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

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 16

Coding Style

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

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

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

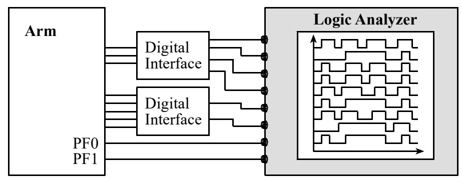
Debugging Tools (1)

- 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)

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.

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.

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

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++;
}
```

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);
}
```


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
```

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` `6800     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`	`GPIO_PORTC_DATA_R |= 0x20;`
`4804     LDR  r0,[pc,#16]    ;r0= 0x400063FC` `6800     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`	`GPIO_PORTC_DATA_R |= 0x40;`

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

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

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

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

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

Performance Instruments (1)

- Independent counter
  - Use internal SysTick timer

```
unsigned long before,elasped;
// 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);
}
```

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++;
}
```

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 31

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;
   }
}
```

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 32

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

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;
}
```

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;
}
```

J. Valvano, A. Gerstlauer
EE445M/ECE380L.12 35

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;
```

Lecture 2 J. Valvano, A. Gerstlauer
EE445M/ECE380L.12 36

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()]++;
}
```


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)

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

Lecture 2 J. Valvano, A. Gerstlauer EE445M/ECE380L.12 39