ESE532: System-on-a-Chip Architecture

Day 26: December 2, 2019

Real Time Scheduling

Today

Real Time
- Synchronous Reactive Model
- Interrupts
  - Polling alternative
  - Timer?
- Resource Scheduling Graphs

Message

- Scheduling is key to real time
  - Analysis
  - Guarantees

Synchronous Circuit Model

- A simple synchronous circuit is a good “model” for real-time task
  - Run at fixed clock rate
  - Take input every cycle
  - Produce output every cycle
  - Complete computation between input and output
  - Designed to run at fixed-frequency
    - Critical path meets frequency requirement

Synchronous Reactive Model

- Discipline for Real-Time tasks
- Embodies “synchronous circuit model”

Synchronous Reactive

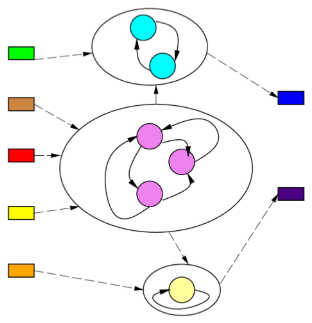
- There is a rate for interaction with external world (like the clock)
- Computation scheduled around these clock ticks (or time-slices)
  - Continuously running threads
  - Each thread performs action per tick
- Inputs and outputs processed at this rate
- Computation can “react” to events
  - Reactions finite and processed before next tick

Thread Form

while (1) { tick(); }

- tick() -- yields after doing its work
  - May be state machine
    - May change state and have different behavior based on state
  - May trigger actions to respond to events (inputs)

Thread Model



Preclass 1

- Typical real-world interaction times?
  - Video frame output?
  - Video game input?
  - Anti-lock brakes, cruise-control?

Tick Rate

- Driven by application – demands of external control
  - Control loop 100 Hz
    - Robot, airplane, car, manufacturing plant
  - Video at 33 fps
  - Game with 20ms response
  - Router with 1ms packet latency
    - 12μs

Tick Rate

- Multiple rates
  - May need master tick as least-common multiple of set of interaction rates
    - …and lower freq. events scheduled less frequently
  - E.g. 100Hz control loop and 33Hz video
    - Master at 10ms
    - Schedule video over 3 10ms time-slots
      - May force decompose into tasks fit into smaller time window since must schedule events at highest frequency

Synchronous Reactive

- Ideal model
  - Per tick reaction (task processing) instantaneous
- Separate function from compute time
- Separate function from technology
  - Feature size, processor mapped to
- Like synchronous circuit
  - If logic correct, works when run clock slow enough
  - Works functionally when change technology
  - Then focus on reducing critical path
    - → making timing work

Timing and Function

- Why want to separate function from technology and timing?
- What happens when get faster (slower) processor?

Synchronous Reactive Timing

- Once functional,
  - need to guarantee all tasks (in all states)
    - Can complete in tick time-slot
    - On particular target architecture
- Identify WCET (worst-case execution time)
  - Like critical path in FSM circuit
  - Time of task on processor target

Preclass 2

- Time available to process objects?

```
tick() {
   for(i=0;i<MAX_OBJECTS;i++)  {
        obj[i].inputs(); // see below
        obj[i].updatePositionState(); // 1,000 cycles
        obj[i].collide(); // 9,000 cycles
        obj[i].render();  // 1,000 cycles
      }
   updateScreen(); // takes 10 ms
}
```

Preclass 2

- Worst-case object processing time?

```
tick() {
   for(i=0;i<MAX_OBJECTS;i++)  {
        obj[i].inputs(); // see below
        obj[i].updatePositionState(); // 1,000 cycles
        obj[i].collide(); // 9,000 cycles
        obj[i].render();  // 1,000 cycles
      }
   updateScreen(); // takes 10 ms
}
// for object class
inputs() {
   int move=getMoveInput(); // 10
   int fire=getFireInput(); // 10
   switch (move){
     case LEFT: moveLeft(); break; // 10
     case RIGHT: moveLeft(); break; // 10
     case FORWARD: thrustIncrease(); break; // 5,000
     case BACK: thrustDecrease(); break; // 4,000
     default:
     }
   if (fire) processFire(); // 10,000
}
```

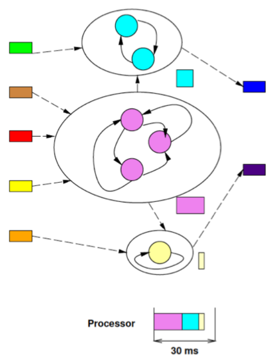
Preclass 2

- Maximum number of objects on single GHz processor?

Synchronous Reactive Timing

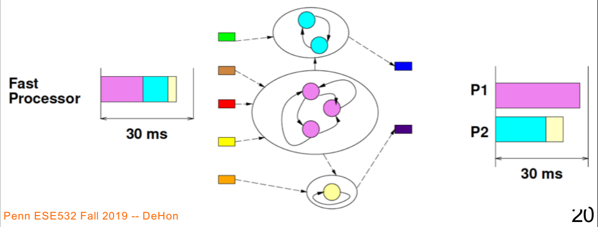
- Once functional,
  - need to guarantee all tasks (in all states) can complete in tick time-slot
  - On particular target architecture
- Identify WCET
  - Like critical path in FSM circuit
  - Time of task on processor target
- Schedule onto platform
  - Threads onto processor(s)

Threads Mapped to Processor



Platforms

- Platform 1: fast processor
- Platform 2: many slow processors



Synchronous Reactive Model

- Discipline for Real-time tasks
- Embodies the "synchronous circuit model"
  - Master clock rate
  - Computation decomposed per clock
  - Functionality assuming instantaneous compute
  - On platform, guarantee runs fast enough to complete critical path at "clock" rate

Interrupts

Interrupt

- External event that redirects processor flow of control
- Typically forces a thread switch
- Common for I/O, Timers
  - Indicate a need for attention

Interrupts

- Why would we use interrupts for I/O?

Interrupts: Good

- Allow processor to run some other work
- Infrequent, irregular task service with low response service latency
  - Low latency
  - Low throughput

Interrupts: Bad

- Time predictability
  - Real-time for computing tasks interrupted
- Processor usage
  - Costs time to switch contexts
- Concurrency management
  - Must deal with tasks executing non-atomically
    - Interleave of interrupted service tasks
    - Perhaps interleave of any task

Interrupted Task

- Add to list

```
atmp=a
new->next =atmp
a=new
```

- Remove from list

```
removed=a->value
rtmp=a->next
a=rtmp
```

- Running something that removes from list
- Interrupt involves adding to list

What can happen?

- Add to list

```
atmp=a
new->next =atmp
a=new
```

- Remove from list

```
removed=a->value
rtmp=a->next
a=rtmp
```

- Sequence

```
remove=a->tmp
rtmp=a->next
– <interrupt>
atmp=a
new->next=atmp
a=new
– <return>
a=rtmp
```

What goes wrong?

Interrupts: Bad

- Time predictability
  - Real-time for computing tasks interrupted
- Processor usage
  - Costs time to switch contexts
- Concurrency management
  - Must deal with tasks executing non-atomically
    - Interleave of interrupted service tasks
    - Perhaps interleave of any task

Polling Discipline

- Alternate to I/O interrupts
- Every I/O task is a thread
- Budget time and rate it needs to run
  - E.g. 10,000 cycles every 5ms
  - Likely tied to
    - Buffer sizes
    - Response latency
- Schedule I/O threads as real-time tasks
  - Some can be DMA channels

IO Thread

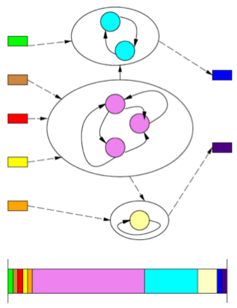
while (1) { process_input(); }

- Like tick() -- yields after doing its work

Preclass 3

- Input at 100KB/s
- 30ms time-slot window
- Size of buffer?
- 100 cycles/byte, GHz processor – runtime of service routine?
  - Fraction of processor capacity?

Scheduling I/O Tasks



Timer Interrupts

- Why do we have timer interrupts in conventional operating systems?
  - E.g. in linux?

Timer Interrupts

- Best effort tasks (i.e. non-real-time tasks)
  - Have no guarantee to finish in bounded time
  - Timer interrupts necessary
    - to allow other threads to run
    - fairness
    - to switch to real-time service tasks
- Need timer interrupts if need to share processor with real-time threads
  - **Alternate:** Easier to segregate real-time and best-effort threads onto different processors

Timer Interrupts?

- Bounded-time tasks
  - E.g. reactive tasks in real-time
  - Task has guarantee to release processor within time window
  - **Not** need timer interrupts to regain control from task
  - (Maybe use deadline operations [Day14] for timer)

Greedy Strategy

- Schedule real-time tasks
  - Scheduled based on worst-case, so may not use all time allocated
- Run best-effort tasks at end of time-slice after complete real-time tasks
  - Timer-interrupt to recover processor in time for start of next scheduling time slot
- (adds complexity)

Real-Time Tasks

- Interrupts less attractive
  - More disruptive
- Scheduled polling better predictability
- Fits with Synchronous Reactive Model

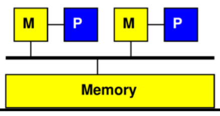
Resource Scheduling Graphs

Scheduling

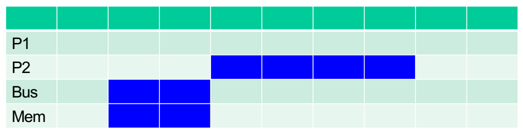
- Useful to think about scheduling a processor by task usage
- Useful to budget and co-schedule required resources
  - Bus
  - Memory port
  - DMA channel

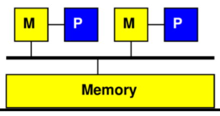
Simple Task Model

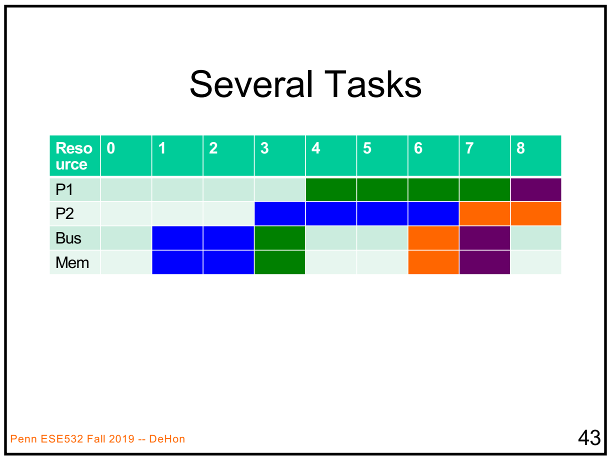
- Task requires
  - Data to be transferred
  - Local storage state
  - Computational cycles
  - (Result data to be transferred)
- Uses resources
  - Bus/channel to transfer data
    - (in and out)
  - Space in memory on accelerator
  - Cycles on accelerator



One Task

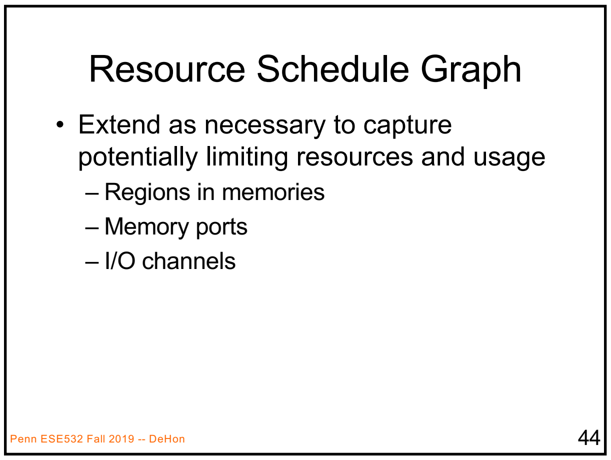






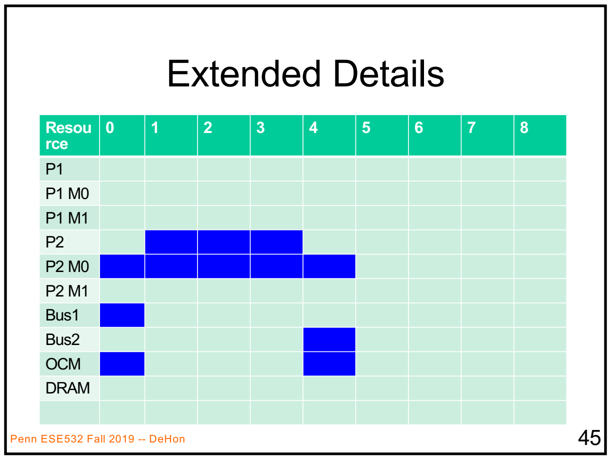
Several Tasks

Resource	0	1	2	3	4	5	6	7	8
P1					🟩	🟩	🟩	🟩	🟪
P2				🟦	🟦	🟦	🟦	🟧	🟧
Bus		🟦	🟦	🟩			🟧	🟪	
Mem		🟦	🟦	🟩			🟧	🟪	



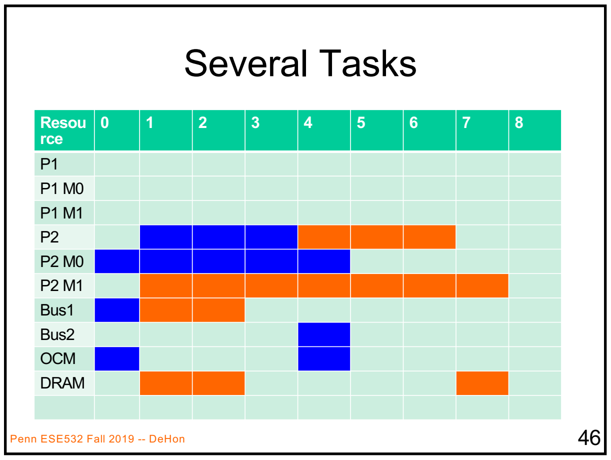
Resource Schedule Graph

- Extend as necessary to capture potentially limiting resources and usage
  - Regions in memories
  - Memory ports
  - I/O channels



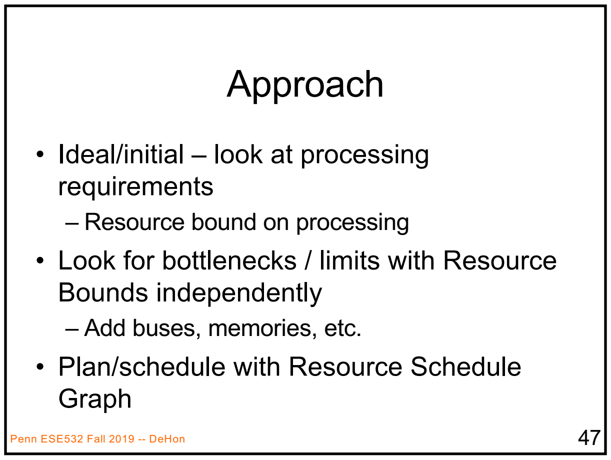
Extended Details

Resource	0	1	2	3	4	5	6	7	8
P1									
P1 M0									
P1 M1									
P2		🟦	🟦	🟦					
P2 M0	🟦	🟦	🟦	🟦	🟦				
P2 M1									
Bus1	🟦								
Bus2					🟦				
OCM	🟦				🟦				
DRAM									



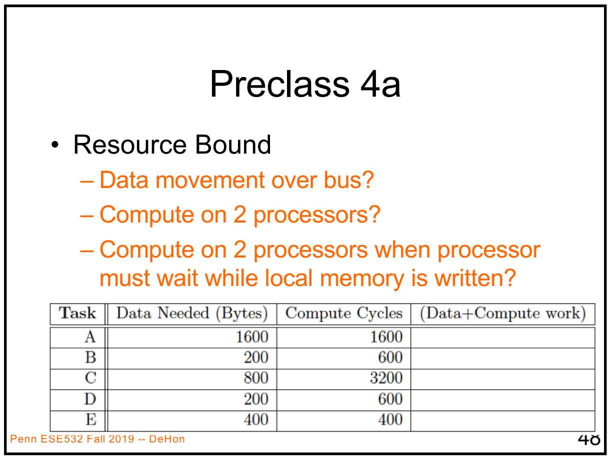
Several Tasks

Resource	0	1	2	3	4	5	6	7	8
P1									
P1 M0									
P1 M1									
P2		🟦	🟦	🟦	🟧	🟧	🟧		
P2 M0	🟦	🟦	🟦	🟦	🟦				
P2 M1		🟧	🟧	🟧	🟧	🟧	🟧	🟧	
Bus1	🟦	🟧	🟧						
Bus2					🟦				
OCM	🟦				🟦				
DRAM		🟧	🟧					🟧	



Approach

- Ideal/initial – look at processing requirements
  - Resource bound on processing
- Look for bottlenecks / limits with Resource Bounds independently
  - Add buses, memories, etc.
- Plan/schedule with Resource Schedule Graph



Preclass 4a

- Resource Bound
  - Data movement over bus?
  - Compute on 2 processors?
  - Compute on 2 processors when processor must wait while local memory is written?

Task	Data Needed (Bytes)	Compute Cycles	(Data+Compute work)
A	1600	1600	
B	200	600	
C	800	3200	
D	200	600	
E	400	400	

Resource Bound wait Transfer

- Total processor cycles when processor must idle during transfer
  - Cycles$_{proc}$ =$\sum(Comp[i] + Bytes[i])$
- RB$_{proc}$=(Cycles$_{proc}$)/2
- RB$_{bus}$= $\sum(Bytes[i])$
- RB=max(Rb$_{bus}$, RB$_{proc}$)

Preclass 4b Schedule

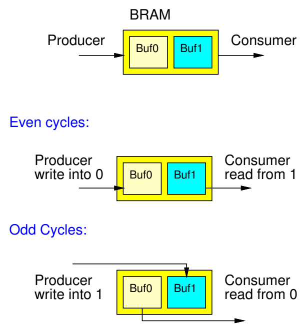
- Processor wait for data load

	200 cycle intervals																															
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Processor 1																																
Processor 2																																
Bus																																

Double Buffering

- Common trick to overlap compute and communication
- Reserve two buffers input (output)
- Alternate buffer use for input
- Producer fills one buffer while consumer working from the other
- Swap between tasks
- Tradeoff memory for concurrency

Double Buffer



Preclass 4c Schedule

- Double Buffer

	200 cycle intervals																															
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Processor 1																																
Processor 2																																
Bus																																

Minimum local memory space required?

Resource Schedule Graphs

- Useful to plan/visualize resource sharing and bottlenecks in SoC
- Supports scheduling
- Necessary for real-time scheduling

Big Ideas:

- Scheduling is key to real time
  - Analysis, Guarantees
- Synchronous reactive
  - Scheduling worst-case tasks “reactions” into master time-slice matching rate
- Schedule I/O with polling threads
  - Avoid interrupts
- Schedule dependent resources
  - Buses, memory ports, memory regions…

Admin

- Project Final Report due Friday