ESE5320: System-on-a-Chip Architecture

Day 26: December 4, 2023

Wrapup

Today

- Part 1:
  - What was course about
  - Final
- Part 2: Review w/ Simple Models
- Part 3
  - Other Courses
  - Questions/Discussion

Goal

- How to design/select/map to SoC to reduce ~~Energy~~/Area/Delay.

Day 1

Outcomes

- Design, optimize, and program a modern System-on-a-Chip.
- Analyze, identify bottlenecks, design-space
- Decompose into parallel components
- Characterize and develop real-time solutions
- Implement both hardware and software solutions
- Formulate hardware/software tradeoffs, and perform hardware/software codesign

Day 1

Outcomes

- Understand the system on a chip from gates to application software, including:
  - on-chip memories and communication networks, I/O interfacing, RTL design of accelerators, processors, firmware and OS/infrastructure software.
- Understand and estimate key design metrics and requirements including:
  - area, latency, throughput, ~~energy, power,~~ predictability, and ~~reliability.~~

Day 2

Message for Day

- Identify the Bottleneck
  - May be in compute, I/O, memory, data movement
- Focus and reduce/remove bottleneck
  - More efficient use of resources
  - More resources
- Repeat

Day 1

Abstract Approach

- Identify requirements, bottlenecks
- Decompose Parallel Opportunities
  - At extreme, how parallel could make it?
  - What forms of parallelism exist?
    - Thread-level, data parallel, instruction-level
- Design space of mapping
  - Choices of where to map, area-time tradeoffs
- Map, analyze, refine

SoC Designer Hardware Building Blocks

- Computational blocks
  - Adders, multipliers, dividers, ALUs
- Data Storage
  - Registers
  - Memory blocks
- Communication blocks
  - Busses
  - Multiplexers, Crossbars
  - DMA Engines
- Processors
- I/O blocks
  - Ethernet, USB, PCI, DDR, Gigabit serial links

Final

Final

- Analysis
  - Bottleneck
  - Amdhal's Law Speedup
  - Computational requirements
  - Resource Bounds
  - Critical Path
  - Latency/throughput/II
- Model/estimate speedup

- From Code
- Forms of Parallelism
- Dataflow, SIMD, VLIW, hardware pipeline, threads, reduce
- Map/schedule task graph to (multiple) target substrates
- Memory assignment and movement
- Area-time points

Final

- Like midterm
  - Content
  - Style
  - No book, notes
  - Calculators allowed (encouraged)
- Previous years final and solutions
- Tuesday, December 19, 3-5pm, Moore 216
- 2 hours (standard final exam period)

Review

Part 2

Sequential Computation

- Computation requires a collection of operations
  - Arithmetic
  - Logical
  - Data storage/retrieval

$$T = \sum T_{op_i}$$

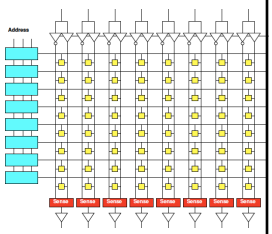
Computations in C

- Express computations in a programming language, such as C
- Can execute computation in many different ways
  - Sequential, parallel, spatial hardware

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Memory Characteristics

- Small memories
  - Fast
  - Low energy
  - Not dense
    - (high area per bit)
- Large memories
  - Slow
  - High energy
  - Dense (less area per bit)



Memory and Compute

- Computation involves both arith/logical ops and memory ops

$$T = \sum T_{op_i}$$

$$T = \sum (op_i == mem) \times T_{mem} + \sum (op_i == alu) \times T_{alu}$$

$$T = N_{memop} \times T_{mem} + N_{alu} \times T_{alu}$$

Memory and Compute

- Computation involves both arith/logical ops and memory ops
- Either can dominate
  - Be bottleneck

$$T = \sum T_{op_i}$$

$$T = N_{memop} \times T_{mem} + N_{alu} \times T_{alu}$$

Memory and Compute

- Timing
  - $T_{mem}=10$
  - $T_{alu}=1$
- $N_{mpy}=$
- $N_{add}=$
- $N_{mem}=$
- Total Time, T?

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

$$T = N_{memop} \times T_{mem} + N_{alu} \times T_{alu}$$

(not count loop, indexing costs in this sequence)

Memory and Compute

- Where bottleneck?
  - T_{mem}=10
  - T_{alu}=1
- N_{mpy}=16
- N_{add}=15
- N_{mem}=95

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

$$T = N_{memop} \times T_{mem} + N_{alu} \times T_{alu}$$

Data Reuse

- Reduce memory operations to large memory by storing in
  - Registers
  - Small memories

$$T = N_{memop} \times T_{mem} + N_{alu} \times T_{alu}$$

$$T = N_{smem} \times T_{smem} + N_{lmem} \times T_{lmem} + N_{alu} \times T_{alu}$$

$T_{lmem} > T_{smem}$

Memory and Compute

- a,b in large mem
- y,z in small mem
  - T_{lmem}=10
  - T_{smem}=1
  - T_{alu}=1
- N_{mpy}=16
- N_{add}=15
- N_{lmem}=?
- N_{smem}=?

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

$$T = N_{smem} \times T_{smem} + N_{lmem} \times T_{lmem} + N_{alu} \times T_{alu}$$

Memory and Compute

- a,b in large mem
- y,z in small mem
  - T_{lem}=10
  - T_{sem}=1
  - T_{alu}=1
- N_{mpy}=16
- N_{add}=15
- N_{lmem}=32
- N_{smem}=63

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

- Performance impact?

$$T = N_{smem} \times T_{smem} + N_{lmem} \times T_{lmem} + N_{alu} \times T_{alu}$$

Task Parallel

- Can run unrelated tasks concurrently

$$T = \sum T_{op_i}$$

$$T = \max\left(\sum T_{op_i}\,(op_i \in Task_1), \sum T_{op_i}\,(op_i \in Task_2)\right)$$

Ideal: T(p) = T(1)/p

Data Parallel

- Can run same task on independent data in parallel

$$T = \sum T_{op_i}$$

Ideal: T(p) = T(1)/p

Data Parallel

- Classify loops?
  - Sequential
  - Data parallel
  - Reduce
  - Parallel prefix

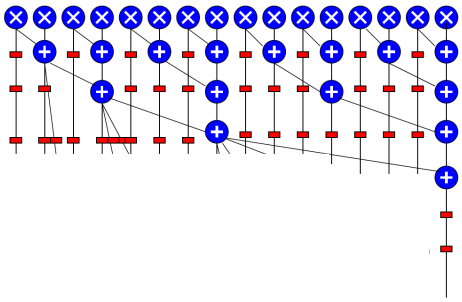
```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Reduce

- (note slightly different second loop)
- Common pattern is a reduce operation
  - Combine a set of data into a single value
- Latency bound for second loop?

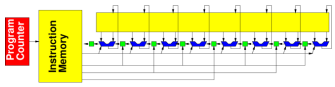
```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z=0;
  for (i=0;i<16;i++)
    z+=y[i];
}
```


Log-Depth Associative Reduce



Vector/SIMD

- Can perform same operation on a set of data items



$$T = \sum T_{op_i}$$

Ideal: T(VL) = T(1)/VL
(Vector Length)

Vector/SIMD

- Can perform same operation on a set of data items
  - Not everything vectorizable

$$T = \sum T_{op_i}$$

$$T = \left(\frac{1}{VL}\right)\sum T_{op_i}\left(\text{vectorize}(op_i)\right) + \sum T_{op_i}\left(\overline{\text{vectorize}(op_i)}\right)$$

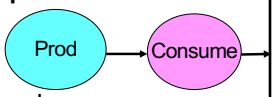
Vector/SIMD

414 total cycles
First loop: 352
Second loop: 62

- What's vectorizable?
- Speedup vector piece VL=4
  - (assume both memory and compute speedup)
- Overall speedup
- Amdahl's Law speedup for VL→infintiy?

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

Dataflow Pipeline



- With no cycles in flowgraph
  - (no feedback)
  - (no loop carried dependencies)
- Producer and consumer can operate concurrently

$$T = \sum T_{op_i}$$

$$T = \max\left(\sum T_{op_i}\,(op_i \in Prod), \sum T_{op_i}\,(op_i \in Consume)\right)$$

Data Flow Pipeline

- Producer/consumer here?
- Time each
  - Assuming T_{mem}=1
- Granularity of dataflow pipeline
- Size of buffer needed to allow concurrent operation?

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Data Flow Pipeline

- (note changed second loop)
- Granularity of dataflow pipeline
- Size of buffer needed to allow concurrent operation?

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[15]=y[15];
  for (i=14;i>=0;i--)
    z[i]=z[i+1]+y[i];
}
```


Spatial Pipeline

- Can build spatial pipeline of hardware operators to compute a dataflow graph

$$T = \sum T_{op_i}$$

- With no feedback: T_{loop}=1
- With feedback limit II: T_{loop}=II_{cycle}

Initiation Interval

- What's II?
  - a, b now Tmem=1
  - Separate memory banks for a,b,z
  - y in local registers
  - z[i-1] communicated through local register

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Initiation Interval

- What's II?
  - a, b, c Tmem=1
  - Separate memory banks for a,b,c,z
  - y in local registers
  - z[i-1] communicated through local register

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i]+c[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```

Initiation Interval

- First loop (Tmem=1)
  - Latency of loop body?
  - II?

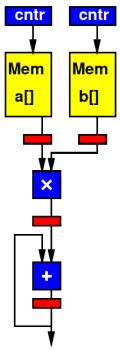
```
while(true) {
    g=0;
    for (i=0;i<16;i++) {
        t=a[i]*b[i]+c[g];
        y[i]=t;
        g=t%16;   }
    z[0]=y[0];
    for (i=1;i<16;i++)
        z[i]=z[i-1]+y[i];
}
```


37

Spatial Pipeline

- Back to original code
- Pipeline taking one a[i], b[i] per cycle
  - Tmem=1
- Cycles to complete?

```
while(true) {
    for (i=0;i<16;i++)
        y[i]=a[i]*b[i];
    z[0]=y[0];
    for (i=1;i<16;i++)
        z[i]=z[i-1]+y[i];
}
```



38

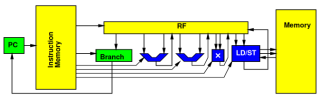
Critical Path

- Critical Path assuming associativity holds?

```
while(true) {
    for (i=0;i<16;i++)
        y[i]=a[i]*b[i];
    z[0]=y[0];
    for (i=1;i<16;i++)
        z[i]=z[i-1]+y[i];
}
```


39

VLIW



- Can control datapath to perform multiple, heterogeneous operations per cycle
  - Tune parallelism
- Op types: A, B, C
  - Ops N_A, N_B, N_C
  - Number of Hardware Units H_A, H_B, H_C
- $T_{RB}=\max(N_A/H_A, N_B/H_B, N_C/H_C,\ldots)\leq T_{VLIW}$
- $T_{CP}\leq T_{VLIW}$

$$T=\sum T_{op_i}$$

40

VLIW

- VLIW
  - 1 load/store (a,b,z)
    - Assume single cycle
  - 1 mpy
  - 1 add
  - (ignoring increment for simplicity/consistency)
  - y/z[i-1] in registers
- RB
- CP

```
while(true) {
    for (i=0;i<16;i++)
        y[i]=a[i]*b[i];
    z[0]=y[0];
    for (i=1;i<16;i++)
        z[i]=z[i-1]+y[i];
}
```


41

VLIW

- VLIW
  - 1 load/store (a,b,z)
    - Assume single cycle
  - 1 mpy
  - 1 add
  - 1 incr

```
while(true) {
    for (i=0;i<16;i++)
        y[i]=a[i]*b[i];
    z[0]=y[0];
    for (i=1;i<16;i++)
        z[i]=z[i-1]+y[i];
}
```

Cycle	mpy	add	Ld/st
0	a*b 0		a1
1		+y[i] 0	b1
2			Z0

42

VLIW

- VLIW
  - 4 load/store (a,b,z)
    - Assume single cycle
  - 2 mpy
  - 2 add
- RB
- CP

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Memory Bottleneck

- Memory can end up being bottleneck

$$T = \sum T_{op_i} = T_{comp} + T_{mem}$$

Ideal: $T(p) = T_{comp}(1)/p + T_{mem}$

Memory Bottleneck

- Pipeline to perform one multiply per cycle
- Memory supplies one data item from large memory (a,b) every 10 cycles
- Performance?
  - (number of cycles)

```
while(true) {
  for (i=0;i<16;i++)
    y[i]=a[i]*b[i];
  z[0]=y[0];
  for (i=1;i<16;i++)
    z[i]=z[i-1]+y[i];
}
```


Memory Bottleneck

- Memory can end up being bottleneck

$$T = \sum T_{op_i} = T_{comp} + T_{mem}$$

Ideal: $T(p) = T_{comp}(1)/p + T_{mem}/Membw$

Memory Bottleneck

- Invest in higher bandwidth
  - Wider memory
  - More memory banks
- Exploit data reuse
  - Smaller memories may have more bandwidth
  - Smaller memories are additional banks
    - More bandwidth

Communication

- Once parallel, communication may be bottleneck

$$T = \sum T_{op_i} = T_{comp} + T_{mem} + T_{comm}$$

- Ideal (like VLIW):
  $T \leq \max(T_{comp}/p, T_{mem}/membw, T_{comm}/netbw)$

Multi-Objective Optimization

- Many forms of parallelism
- Given fixed area (resources, energy)
  - Maximize performance
  - Select best architecture
- Given fixed performance goal (Real Time)
  - Find architecture that achieves
  - With minimum area (energy, cost)

Other Courses Wrapup, Questions

Part 3

Distinction

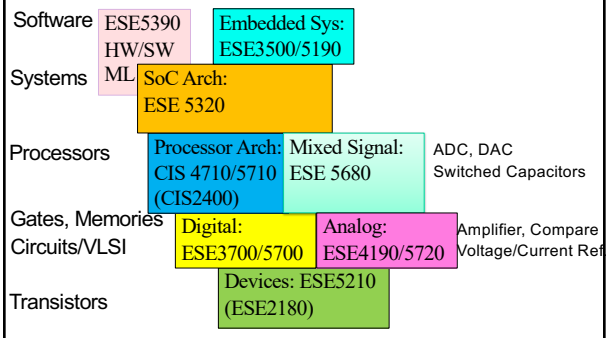
CIS2400, 5710(4710)

- Best Effort Computing
  - Run as fast as you can
- Binary compatible
- ISA separation
- Shared memory parallelism
- Caching – automatic memory management
- Superscalar
- Pipelined processor

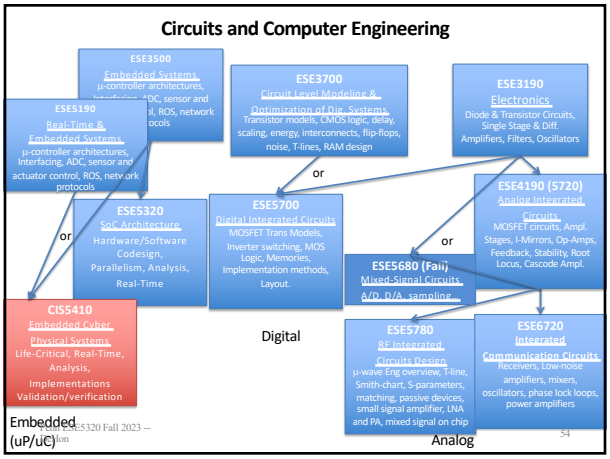
ESE5320

- Hardware-Software codesign
  - Willing to recompile, maybe rewrite code
  - Define/refine hardware
- Real-Time
  - Guarantee meet deadline
- Non shared-memory models
- Explicit memory management
- VLIW

Abstraction Stack



All about CHIPS, ICs



Other Courses

- Security: CIS3310, CIS5510
  - ESE6800 (this Spring): Hardware Security
- Networking: ESE4070, CIS5530
- GPGPU (graphics focus): CIS5650
- Machine Learning: ESE5390
- Power Electronics: ESE5800

Message

- Any interesting, challenging computation will require both hardware and software
- SoC powerful implementation platform
  - Target pre-existing
  - Design customized for problem
  - Exploit heterogeneous parallelism
- Understand and systematically remove bottlenecks
  - Compute, memory, communicate, I/O

56

Admin

- Feedback (including P1)
- Project
  - Demo Day Monday, Dec. 11th
    - With board return
    - Signup for slot
  - Reports due Dec. 11th
- No DQ today
- Optional lecture (Real Time) on Wednesday
- Review: watch Ed Discuss
- Final: Tuesay, Dec. 19, 3pm, Moore 216

57

Question/Discussion

58