EEL 4783: Hardware/Software Co-design with FPGAs

Lecture 11: Hardwar/Software Partitioning *

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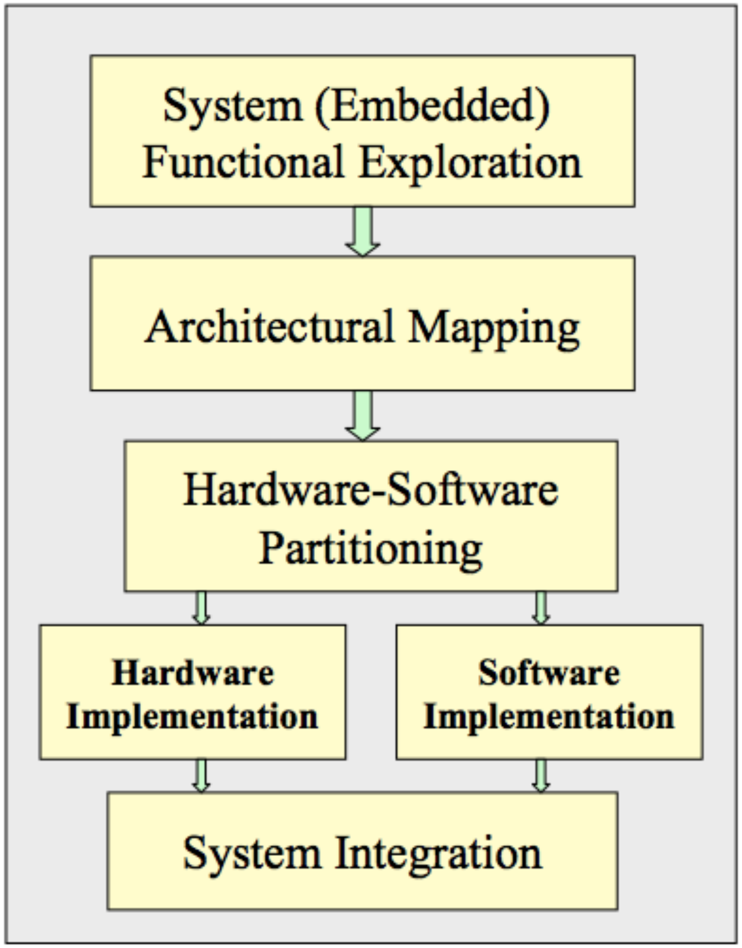
Stands For Opportunity

* Adopted from G. Khan COE718:

Embedded Computing System

- HW and SW used to be designed separately
- Co-Design an increasingly important object, because
  - Performance
  - Cost
  - Complexity
  - ?

HW/SW Co-Design



- Functional exploration: Define a desired product's requirements and produce a specification of the system behavior.
- Map this specification
- Partition the functions between silicon and code, and map them
- Integrate system

HW/SW Co-Design

- Co-Specification: Describe system functionality at the abstract level
- System description is converted into a task graph representation
- HW-SW Partitioning: Take the task graph and decide which components are implemented where/how ?
  - i.e. Dedicated hardware Software

HW/SW Co-Design

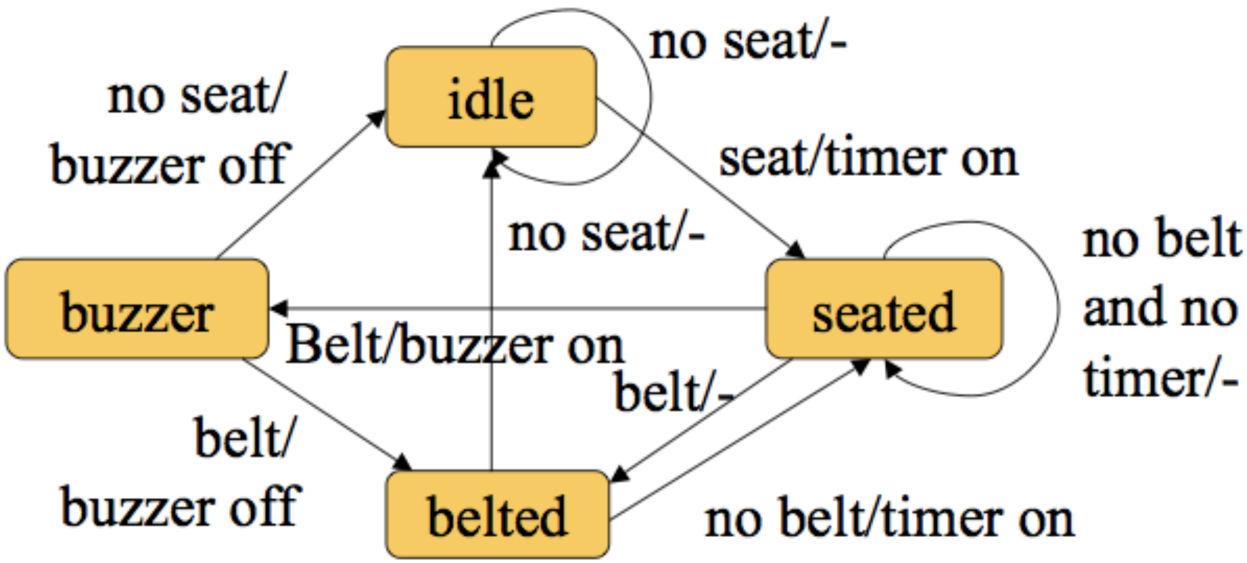
- Both textual and graphical representation like DAG are used to describe system.
- Analyzes task graph to determine each task's placement
- Many partitioning algorithms being developed
- Major problem involves the computation time of the algorithm.

System Design Patterns

- Design Pattern: A generalized description of the design of a certain type of program that can also be used for system representation and hardware-software partitioning.

- State Diagram
  Data Flow Graph
  Control Data Flow Graph (CDFG)
  - Others
    Directed Acyclic Graph (DAG) similar to DFG
    Directed Acyclic Data Dependence Graph with Precedence (DADGP)

State Machine: Seat-belt System




```
switch (state) {
    case IDLE: if (seat) { state = SEATED; timer_on = TRUE; } break;
    case SEATED: if (belt) state = BELTED;
                    else if (timer) state = BUZZER; break;
    … … …
}
```

Data Flow Graph (DFG)

- DFG does not represent control
- It models the Basic Block: code or a system block with one entry and exit
- Describes the minimal ordering requirements on operations

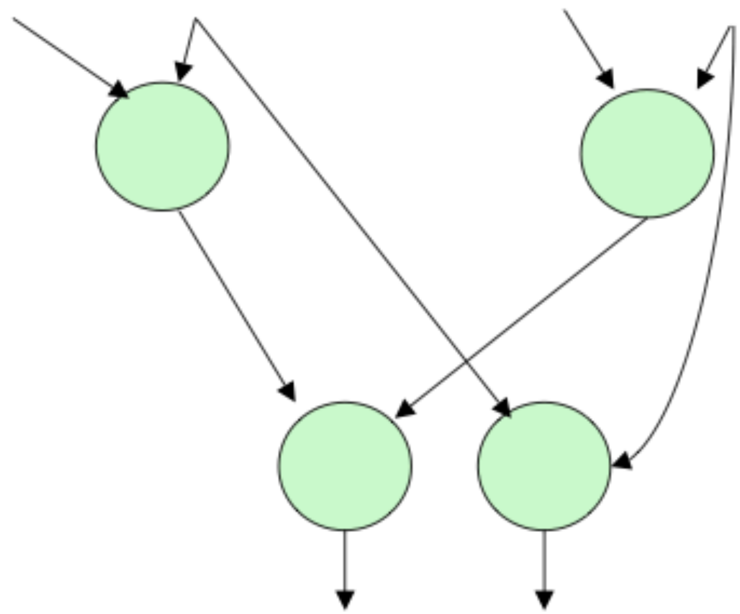
Data Flow Graph: Software Module

$x = a + b;$

$y = c - d;$

$z = x * y;$

$y1 = b + d;$



DFG

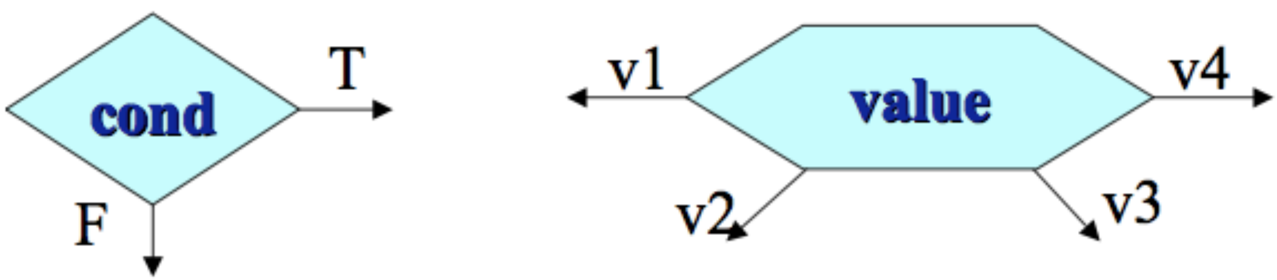
Control Data Flow Graph

CDFG: represents control and data.

- Uses data flow graphs as components.
- Two types of nodes:
  - **Data Flow Node encapsulate a DFG**

    x = a + b;
    y = c + d

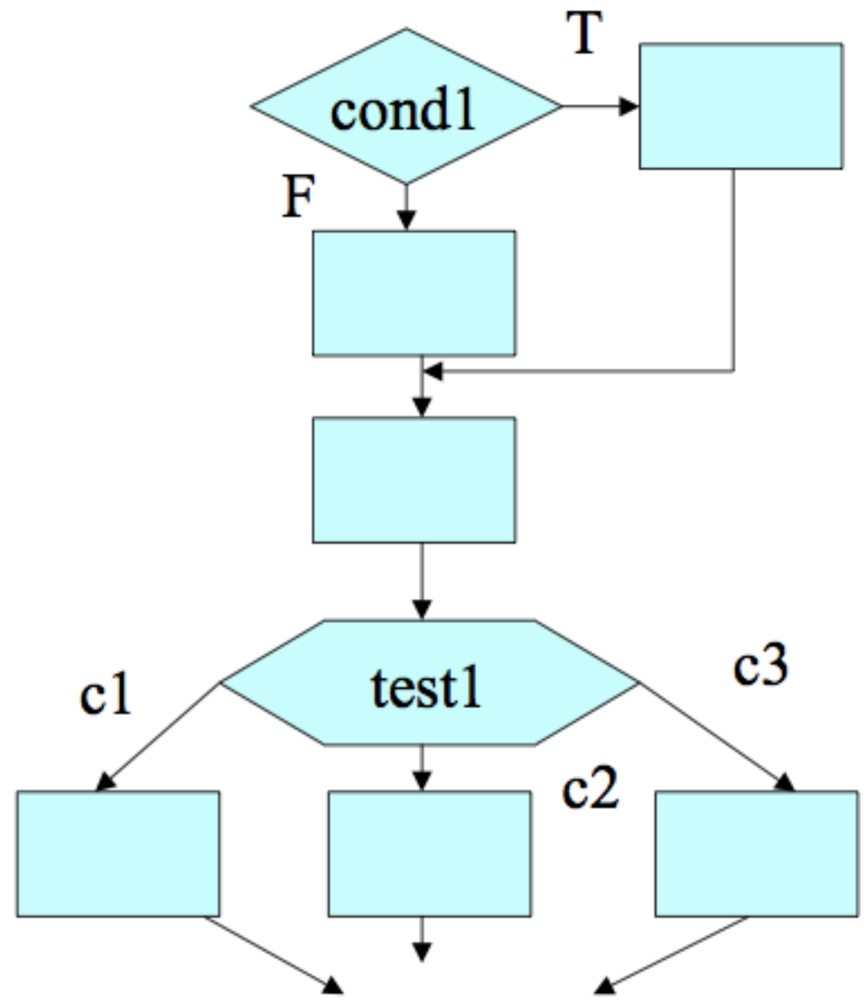
  - **Decision Nodes**



Equivalent Forms

Control Data Flow Graph Example

```
if (cond1) bb1();
 else bb2();
bb3();
switch (test1) {
    case c1: bb4(); break;
    case c2: bb5(); break;
    case c3: bb6(); break;
}
```



Scheduling and Partitioning

- The main input to scheduling for partitioning is a graph representation in the form of DFG.

- Complex designs contain thousands of both control and data processing operations ranging from:
  - Complex arithmetic operations or logic-level bit- operations.
  - All the above interleaved operations by multiple control operations and loops.

- Such designs contain thousands of data-dependencies, basic blocks and control paths.

DFG-based Scheduling & Partitioning

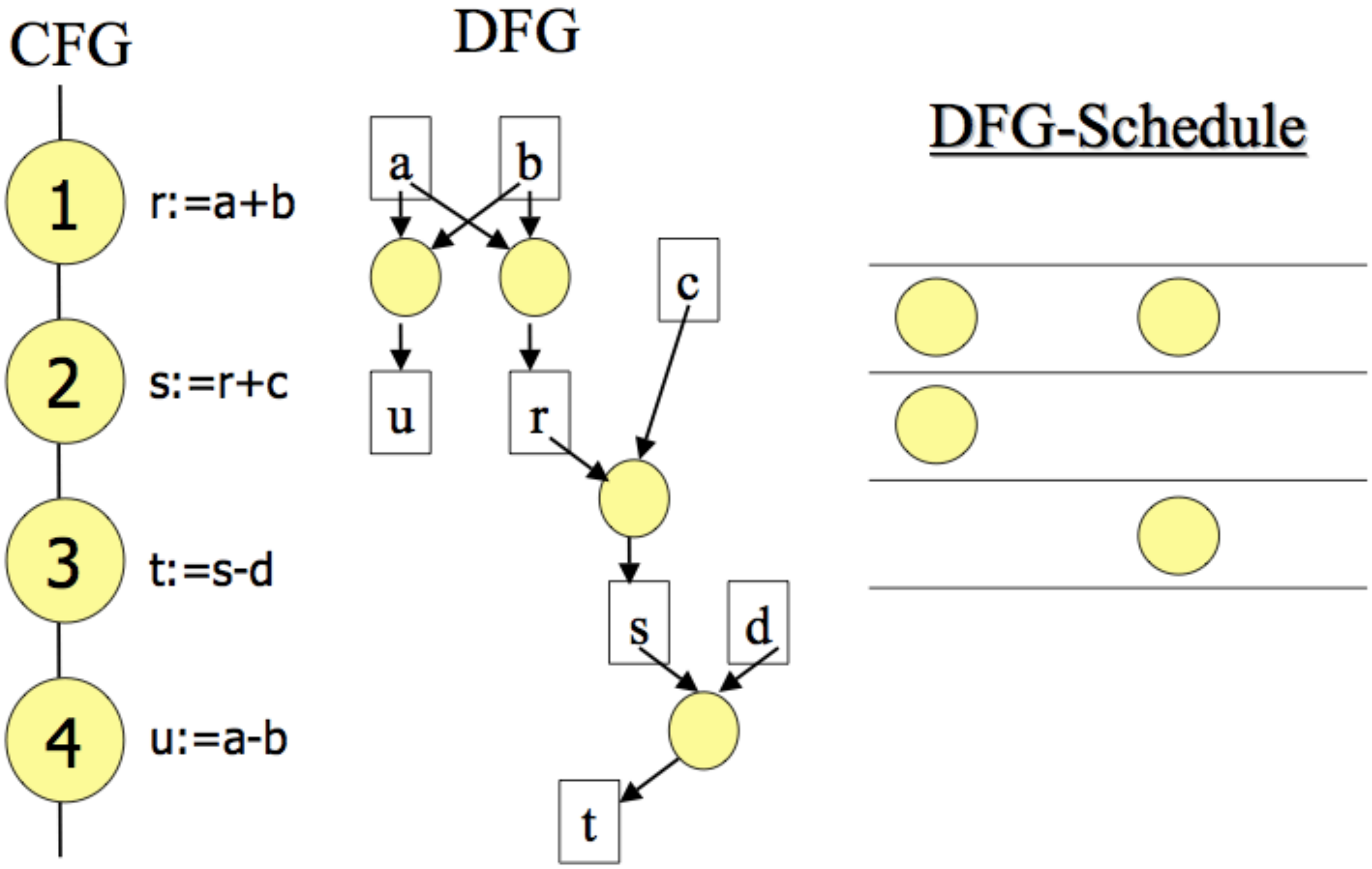
- Data-flow based scheduling techniques extract parallelism from the input description
- Schedule operations in parallel to satisfy the constraints.
- Two most common DF-based scheduling methods.
  - List Scheduling (LS): Minimize the number of control steps under resource constraints.
  - Force-directed Scheduling (FDS): Minimize the number of resource constraints under a fixed number of control steps.

Data Flow: DF-Scheduling

- List scheduling algorithm uses a cost function to select the operation to be scheduled from a list.
- DF-approach provides flexible cost function and it can be easily adapted to generate resource-constraint as well as time-constraint schedules.

- The cost function can represent any design measure such as HW area, delay, etc.
- The result is only as good as the cost function.
- DF-based algorithms can analyze all the parallelism in the DFG independently.

DF- Scheduling Example



Control Flow: CF-Scheduling

- Analyze the sequences of operations in CFG called control flow paths and schedule the CFG with minimum number of control steps in each path.
- Path-based scheduling is one of the main example of this scheme.
- Analyze all the paths in the CFG and schedule each of them independently.
- It minimizes the number of control steps in each path rather than minimizing the number of states.
- Paths in CFG come from loops and conditional operations.

Partitioning Approaches

- Simple one CPU and single ASIC architecture is the most common.

- Early approaches Initially assume all tasks mapped to software
- Move tasks to HW incrementally until system requirements are met.

- Other early approaches: Initially all tasks are mapped to dedicated hardware.
- Move tasks incrementally to SW until system requirements are met.

Optimal Partitioning

- Exhaustiveapproachesarecharacterizedbyattempting all possible combinations there by always selecting the best option.
- Exhaustiveapproachesaregenerallycomputationally intensive, consume huge-time in the range of hours or even days to find an optimal partition.
- Limitedtosmallertaskgraphs
  – Large telecom or other embedded systems can have upto 4000 nodes

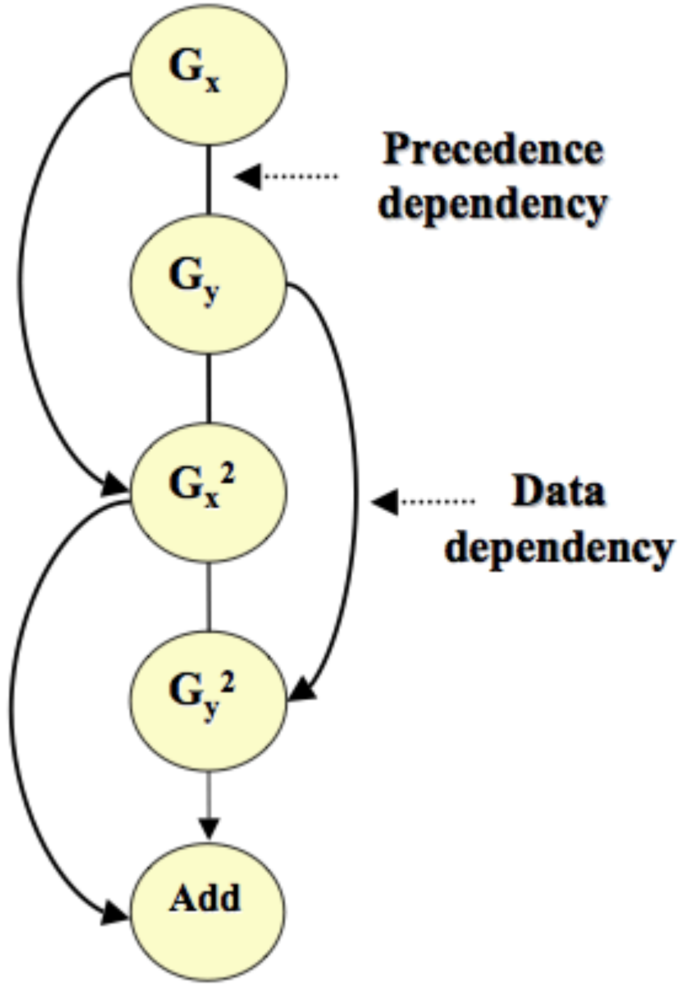
Edge Detection Example

Pair of masks are convolved to estimate gradients, G_x and G_y

Overall $\mathbf{G^2 = (G_x^2 + G_y^2)}$

HW-SW Library

Operation	SW EXE (ms)	HW EXE (ms)	HW Area (gates)
Gradient (Gx or Gy)	9.4	1.4	1200
Square	5.2	0.9	500
Add	3.88	0.3	100



SOBEL Edge Detection

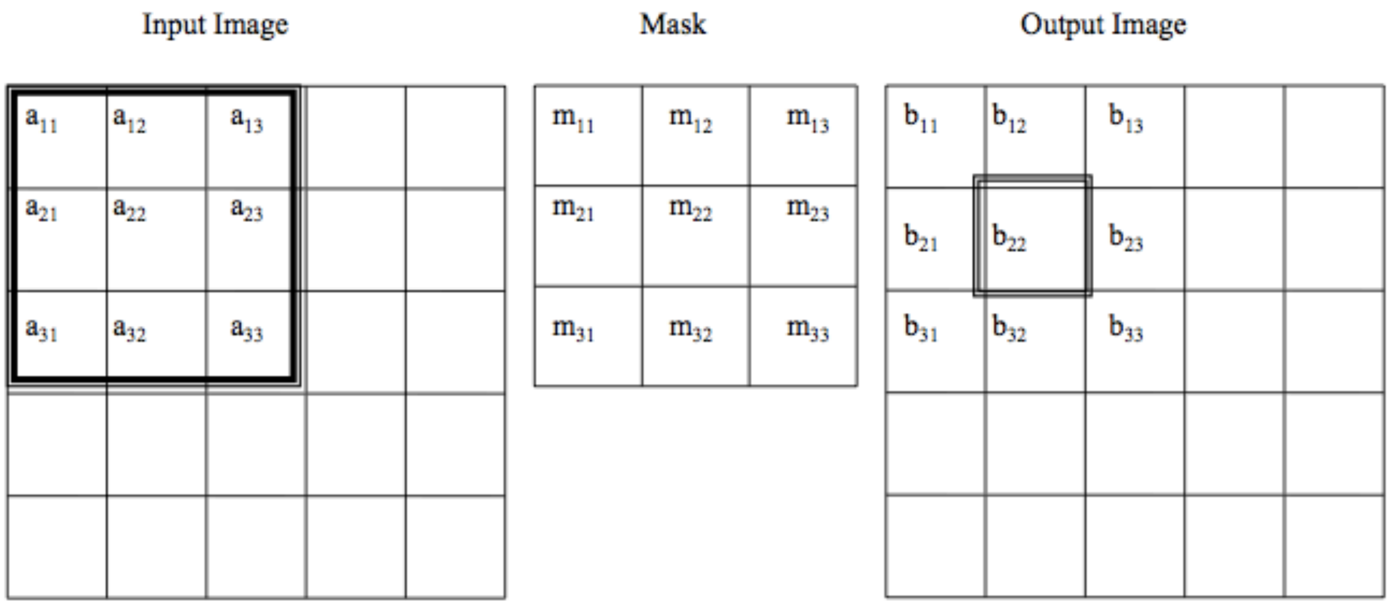
SOBEL masks

-1	0	+1
-2	0	+2
-1	0	+1

Gx

+1	+2	+1
0	0	0
-1	-2	-1

Gy

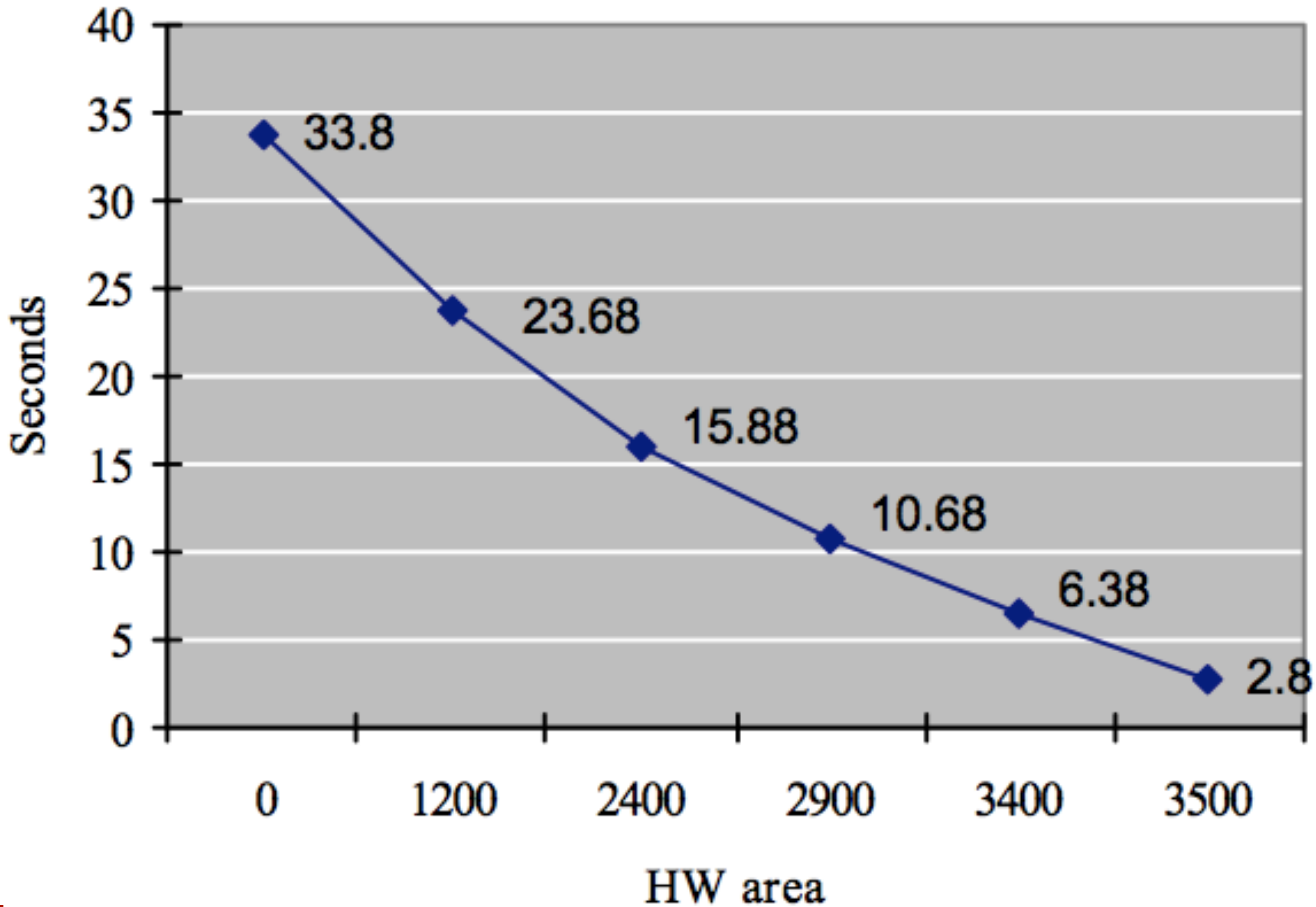


$$b_{22}=(a_{11}*m_{11})+(a_{12}*m_{12})+(a_{13}*m_{13})+(a_{21}*m_{21})+(a_{22}*m_{22})+(a_{23}*m_{23})+(a_{31}*m_{31})+(a_{32}*m_{32})+(a_{33}*m_{33})$$

SOBEL Edge Detection

```
main() {
unsigned char image_in[ROWS][COLS];
unsigned char image_out[ROWS][COLS];
int r, c; /* row and column array counters */
int pixel; /* temporary value of pixel */
         /*filter the image and store result in output array */
for (r=1; r<ROWS-1; r++)
 for (c=1; c<COLS-1; c++) {   /* Apply Sobel operator. */
   pixel = image_in[r-1][c+1]-image_in[r-1][c-1]
         + 2*image_in[r][c+1] - 2*image_in[r][c-1]
         + image_in[r+1][c+1] - image_in[r+1][c-1];
   /* Normalize and take absolute value */
   pixel = abs(pixel/4);
   /* Check magnitude */
   if (pixel > Threshold)
   pixel= 255; /*EDGE_VALUE;*/
   /* Store in output array */
   image_out[r][c] = (unsigned char) pixel;
 }
}
```

SOBEL Edge Detection



Final issues

- Come by my office hours (right after class)
- Any questions or concerns?