ECPS 203
Embedded Systems Modeling and Design
Lecture 19

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Lecture 19: Overview

- Course Administration
  - Final course evaluation
  - Final exam
- Project Discussion
  - A1: Introduction of Canny Edge Detector application
  - A2: Clean C++ model with static memory allocation
  - A4: From single image to video stream processing
  - A5: Test bench model in SystemC
  - A6: Structural DUT module and algorithm profiling
  - A7: Performance measurement on prototyping board
  - A8: Pipelined and parallel model with back-annotated timing
  - A9: Throughput optimization by pipeline load balancing
    - ➢ Discussion

Course Administration

- Final Course Evaluation
  - Open until end of 10th week (Sunday night)
  - Nov. 25, 2019, through Dec. 8, 2019, 11:45pm
  - Online via EEE Evaluation application
- Mandatory Evaluation of Course and Instructor
  - Voluntary
  - Anonymous
  - Very valuable
- Please spend 5 minutes for this survey!
  - Your feedback is appreciated!

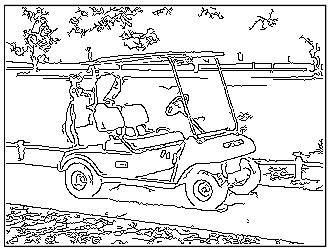
Course Administration

- Final Exam
  - Allocated time
    - Monday, December 9, 2019, 8:00-10:00am
  - Location
    - Regular classroom, DBH 1200
  - Format: Written Exam
    - Exam sheet with questions
    - Answers to be filled in
    - Open notes, open course materials
    - Open laptop, open browser, open server login
    - No emails, no instant messaging!

ECPS 203 Project

- Application Example: Canny Edge Detector
  - Embedded system model for image processing: Automatic edge detection in a digital camera

golfcart.pgm



golfcart.pgm_s_0.60_l_0.30_h_0.80.pgm

  - Application source and documentation:
    - John Canny, *"A Computational Approach to Edge Detection"*, IEEE TPAMI, 1986.
    - http://en.wikipedia.org/wiki/Canny_edge_detector
    - ftp://figment.csee.usf.edu/pub/Edge_Comparison/source_code/canny.src

Project Assignment 1

- Task: Introduction to Application Example
  - Canny Edge Detector
  - Algorithm for edge detection in digital images
- Steps
  1. Setup your Linux programming environment
  2. Download, adjust, and compile the application C code with the GNU C compiler (**`gcc`**)
  3. Study the application, determine function-call tree
- Deliverables
  - Source code and text file: **`canny.c`**, **`canny.txt`**
- Due
  - Wednesday, October 9, 2019, 6pm

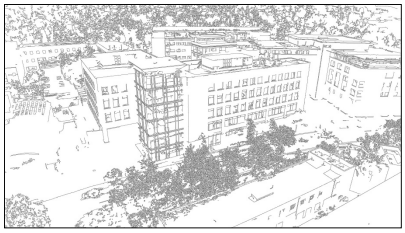
Project Assignment 2

- Task: Clean C++ model with static memory allocation
  - Prepare the C++ source code for modeling in SystemC
  - Configure parameters for specific application
  - Apply static memory allocation
- Steps
  1. Fix the off-by-one bug in the **`non_max_supp`** function
  2. Clean-up the code for compilation without warnings
  3. Fix configuration parameters to compile-time constants
  4. Remove or replace dynamic memory allocation
- Deliverables
  - Source code and text file: **`canny.cpp`**, **`canny.txt`**
- Due
  - Wednesday, October 16, 2019, 6pm

ECPS 203 Project

- Application Example: Canny Edge Detector
  - Embedded system model for image processing:
    Automatic edge detection in a video camera of a drone

Engineering012.png



Engineering012_edges.pgm

  - Video taken by a drone flying over UCI Engineering Plaza
    - Available on the server: **`~ecps203/public/DroneFootage/`**
    - High resolution, 2704 by 1520 pixes
    - Representative sample, using 30 extracted frames for test bench model

Project Assignment 4

- Task: From Single Image to Video Stream Processing
  - Prepare a sequence of image frames from the video
  - Convert the Canny application to process the video frames
- Steps
  1. Extract 30 of video frames suitable for use in a test bench
  2. Convert the color frames to grey-scale images in PGM format
  3. Recode your Canny C++ model to process the video frames
     - To run Canny application successfully, increase stack size
     - Adjust Canny parameters for the "best looking" output images
- Deliverables
  - Source code and text file: **`Canny.cpp`**, **`Canny.txt`**
- Due
  - Wednesday, October 30, 2019, 6pm

Project Assignment 4

- Task: From Single Image to Video Stream Processing
  - Prepare a sequence of image frames from the video
  - Convert the Canny application to process the video frames
- Bonus (20% extra credit)
  1. Take your own video (e.g. with your phone camera)
  2. Cut out a short sequence of 30 frames
  3. Convert the resolution to 2704x1520 pixels (or similar)
  4. Follow the regular steps outlined on the previous slide
  5. Make the frames available to TA for grading
     - **`mkdir ~/video/`**
     - Store frames in the directory
     - **`chmod -R ugo+rX ~/video/`**

Project Assignment 5

- Task: Test bench for the Canny Edge Detector
  - Convert C++ model to SystemC model
  - Add a test bench structure around the C++ model
  - Wrap DUT into a platform model with explicit I/O units
- Steps
  1. Create test bench structure: Stimulus, Platform, Monitor
  2. Create platform model: DataIn, DUT, DataOut
  3. Localize functions and use **`sc_fifo`** channels for communication
     - Pay attention to stack sizes for every thread
- Deliverables
  - SystemC source code and text file: **`Canny.cpp`**, **`Canny.txt`**
- Due
  - Wednesday, November 6, 2019, 6pm

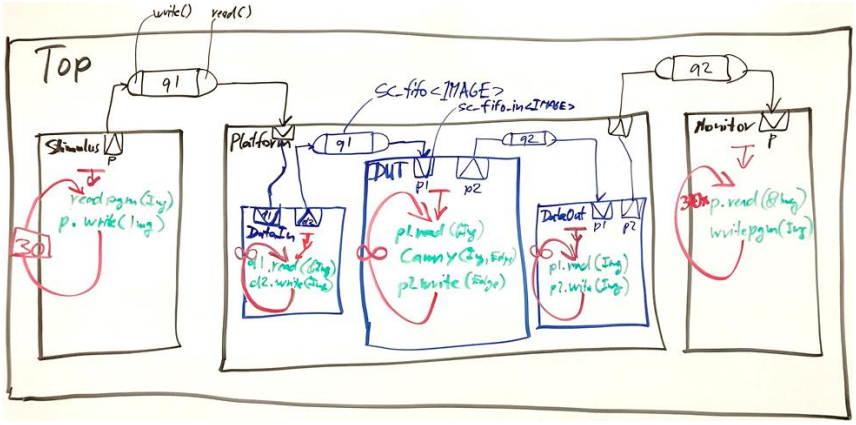
Project Assignment 5

- Task: Test bench for the Canny Edge Detector
  - Expected instance tree

```
Top top
|------ Monitor monitor
|------ Platform platform
|       |------ DUT canny
|       |------ DataIn din
|       |------ DataOut dout
|       |------ sc_fifo<IMAGE> q1
|       \------ sc_fifo<IMAGE> q2
|------ Stimulus stimulus
|------ sc_fifo<IMAGE> q1
\------ sc_fifo<IMAGE> q2
```

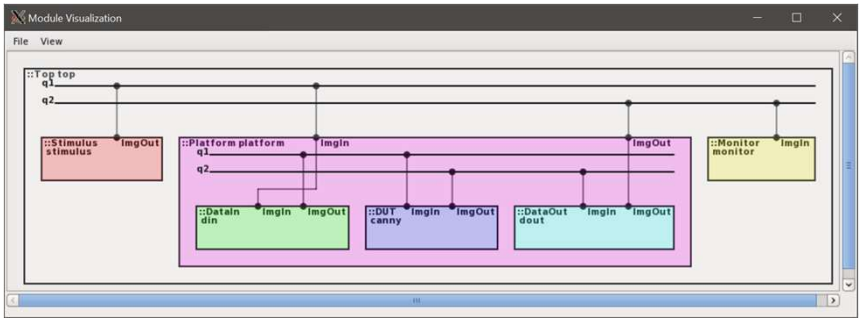
Project Assignment 5

- Task: Test bench for the Canny Edge Detector
  - Discussion on whiteboard: Top-level and Platform structure



Project Assignment 5

- Task: Test bench for the Canny Edge Detector
  - Expected graphical structure with RISC v0.5.0 **`visual`** tool



Project Assignment 6

- Task: Structural refinement of the DUT module
  - Refine the structural hierarchy of the DUT module
  - Refine the structural hierarchy of the Gaussian Smooth module
  - Profile the relative complexity of the Canny functions
- Steps
  1. Create structure in DUT: Gaussian Smooth, …, Apply Hysteresis
  2. Create structure in Gaussian Smooth: Input, Gauss, BlurX, BlurY
  3. Profile the algorithm, obtain relative computational complexity
- Deliverables
  - **`Canny.cpp`** (refined structural model)
  - **`Canny.txt`** (profile of relative complexity of the DUT modules)
- Due
  - Wednesday, November 13, 2019, 6pm

Project Assignment 6

- Step 1: Refined structure of the DUT module
  - Expected module instance tree

```
Platform platform
|------ DataIn din
|------ DUT canny
|       |------ Gaussian_Smooth gaussian_smooth
|       |------ Derivative_X_Y derivative_x_y
|       |------ Magnitude_X_Y magnitude_x_y
|       |------ Non_Max_Supp non_max_supp
|       \------ Apply_Hysteresis apply_hysteresis
\------ DataOut dout
```

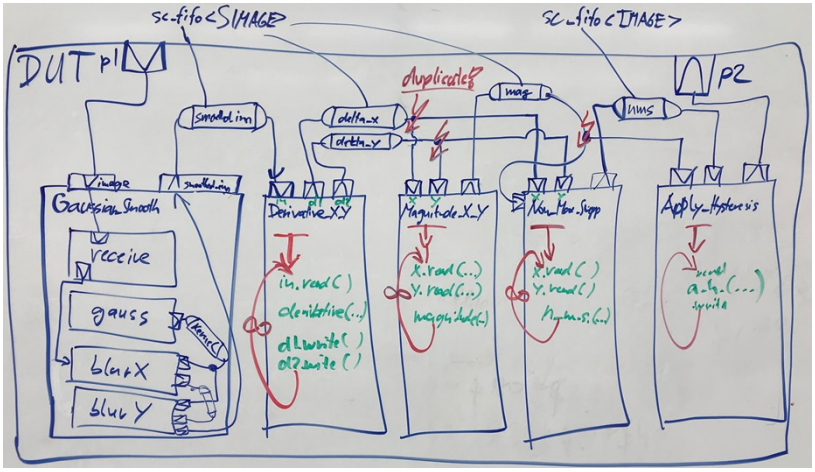
Project Assignment 6

- Step 2: Refined structure of the Gaussian Smooth block
  - Expected module instance tree

```
DUT canny
|------ Gaussian_Smooth gaussian_smooth
|       |------ Receive_Image receive
|       |------ Gaussian_Kernel gauss
|       |------ BlurX blurX
|       \------ BlurY blurY
|------ Derivative_X_Y derivative_x_y
|------ Magnitude_X_Y magnitude_x_y
|------ Non_Max_Supp non_max_supp
\------ Apply_Hysteresis apply_hysteresis
```


Project Assignment 6

- Task: Structural model of the Canny Edge Detector
  - Discussion on whiteboard: Refined DUT structure



Project Assignment 6

- Task: Structural model of the Canny Edge Detector
  - Expected DUT structure with RISC v0.5.0 **`visual`** tool

Project Assignment 6

- Step 3: Profile the Canny functions
  - ➢ Performance profiling of the Canny Edge Detector
  - ➢ Determine the relative complexity of the Canny functions
    - Is there any performance bottleneck?
    - If so, where?
  - Use the GNU C/C++ profiling tools
    - ➢ **`g++ -pg`**
    - ➢ **`gprof`**
    1. Compile the SystemC source code with option **`-pg`**
    2. Run the simulation once with instrumentation, obtain **`gmon.out`**
    3. Run the profiler: **`gprof Canny`**
    4. Validate the reported call tree
    5. Analyze the “flat profile” for the DUT components (**`self`**)

Project Assignment 6

- Step 3: Profile the Canny functions, obtain relative computational complexity
  - Profiled complexity comparison (in **`Canny.txt`**):

```
Gaussian_Smooth                    40.57%
|------ Gaussian_Kernel    0.00%
|------ BlurX              17.23%
\------ BlurY              23.34%
Derivative_X_Y              6.26%
Magnitude_X_Y              15.90%
Non_Max_Supp               23.98%
Apply_Hysteresis           12.29%
                           100%
```

  - ➢ Profiling results vary, but Gaussian Smooth is a bottleneck!

Project Assignment 7

- Task: Performance measurement on prototyping board
  - Run C++ model of Canny Edge Detector on Raspberry Pi
  - Obtain absolute timing measurements of Canny functions
- Steps
  1. Prepare the prototyping board with Raspbian operating system
  2. Upload **`Canny.cpp`** from Assignment 4 and compile it
  3. Instrument the source code with real-time measurements
  4. Note the computation delays of the major Canny functions
- Deliverables
  - **`Canny.cpp`** (model instrumented with timing measurements)
  - **`Canny.txt`** (table of measured delays)
- Due
  - Wednesday, November 20, 2019, 6pm

Project Assignment 7

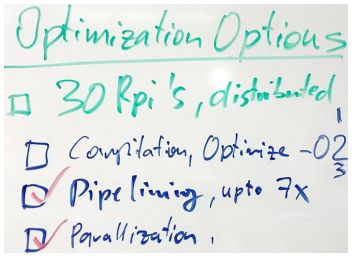
- Task: Performance measurement on prototyping board
  - Measured delays on Raspberry Pi 3 (in `Canny.txt`):

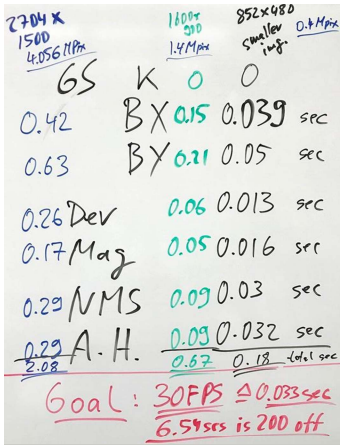
```
Gaussian_Smooth                  3.53 sec
|------ Gaussian_Kernel  0.00 sec
|------ BlurX             1.71 sec
\------ BlurY             1.82 sec
Derivative_X_Y                   0.48 sec
Magnitude_X_Y                    1.03 sec
Non_Max_Supp                     0.83 sec
Apply_Hysteresis                 0.67 sec
TOTAL                            6.54 sec
```

  - ➢ This performance is far too slow for real-time video!
  - ➢ Discussion: What options exist to speed this up?

Project Assignment 7

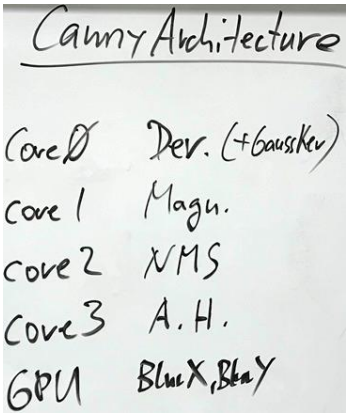
- Discussion: Measured delays on Raspberry Pi ~~3~~ **4**
  - **TOTAL** ~~**6.54 seconds**~~
  - ➢ This performance is far too slow for real-time video!
  - ➢ Discussion: What options exist to speed this up?

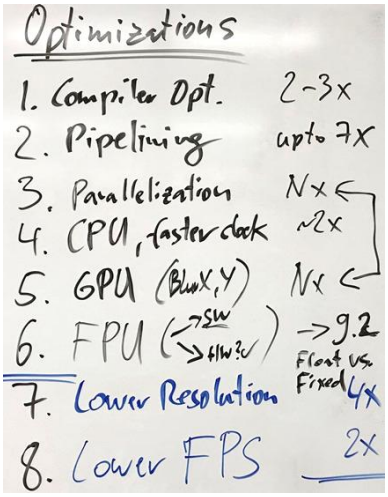




Project Assignment 7

- Discussion: Performance Improvement Options



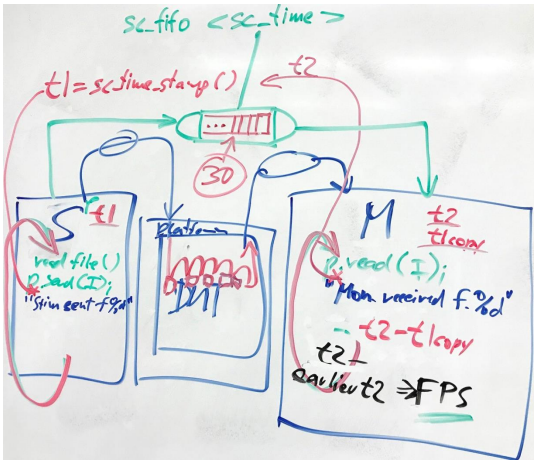


Project Assignment 8

- Task: Pipelining and parallelization of the DUT module
  - Back-annotate estimated delays to observe timing in the model
  - Pipeline and parallelize the model to improve throughput
- Steps
  1. Instrument model with simulated time to observe frame delay
  2. Back-annotate estimated timing into DUT components
  3. Improve test bench to observe frame throughput
  4. Pipeline the DUT into a sequence of 7 stages with buffer size 1
  5. Slice the BlurX and BlurY modules into 4 parallel threads
- Deliverables
  - **`Canny.cpp`**: pipelined and parallelized SystemC model
  - **`Canny.txt`**: table of observed frame delays and throughput
- Due: Wednesday, November 27, 2019, 6pm

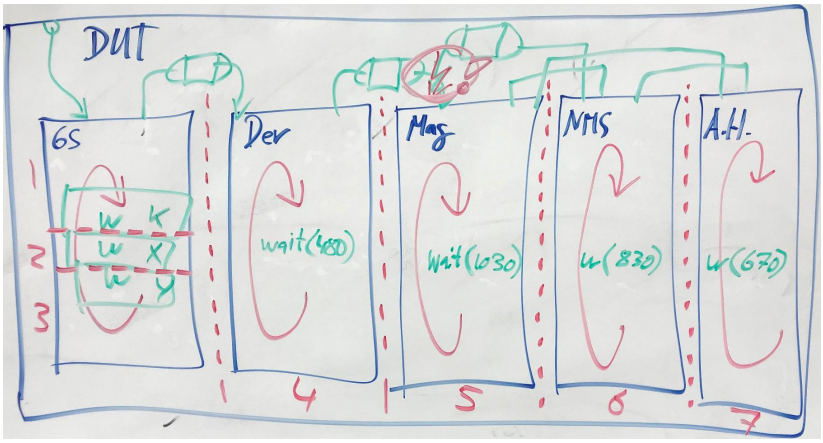
Project Assignment 8

- Timed test bench model for the Canny Edge Detector
  - Discussion on whiteboard: Chart of refined test bench structure



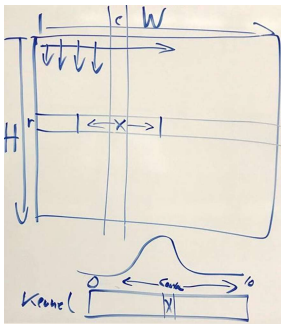
Project Assignment 8

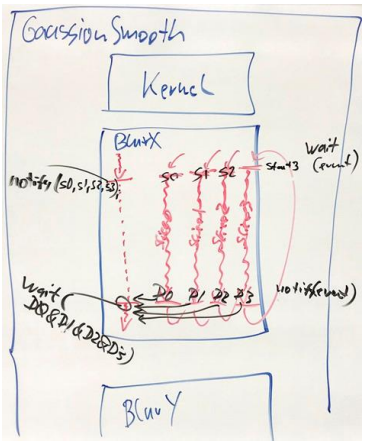
- Pipelined and parallel model of the Canny Edge Detector
  - Discussion on whiteboard: Chart of pipelined DUT structure



Project Assignment 8

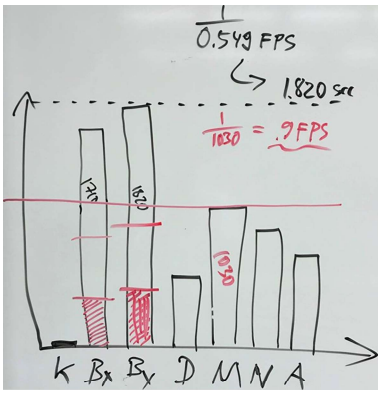
- Pipelined and parallel model of the Canny Edge Detector
  - Discussion on whiteboard: Parallel BlurX, BlurY functions (step 5)

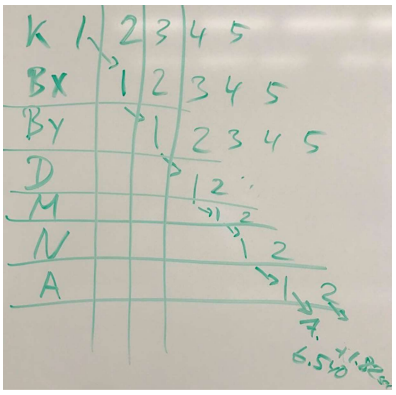




Project Assignment 8

- Pipelined and parallel model of the Canny Edge Detector
  - Discussion on whiteboard: Parallel BlurX, BlurY functions (step 5)





Project Assignment 8

- Pipelined and parallel model of the Canny Edge Detector
  - Back-annotation of measured timing delays
  - ➢ 4-way parallelization of BlurX and BlurY modules (step 5)

Receive, Make_Kernel	0 ms	0 ms
BlurX	1710 ms	427 ms
BlurY	1820 ms	455 ms
Derivative_X_Y	480 ms	480 ms
Magnitude_X_Y	1030 ms	1030 ms
Non_Max_Supp	830 ms	830 ms
Apply_Hysteresis	670 ms	670 ms
	=======	=======
TOTAL:	6540 ms	3892 ms
	=======	=======
Throughput:	1/1820ms	1/1030ms
	0.549 FPS	0.971 FPS

Project Assignment 8

- Pipelined and parallel model of the Canny Edge Detector
  - Expected execution log with timing (after step 5)

```
    0 s: Stimulus sent frame  1.
    0 s: Stimulus sent frame  2.
    0 s: Stimulus sent frame  3.
[...]
3422 ms: Stimulus sent frame 16.
3892 ms: Monitor received frame  1 with  3892 ms delay.
[...]
30672 ms: Monitor received frame 27 with 15920 ms delay.
30672 ms: 1.030 seconds after previous frame, 0.971 FPS.
31702 ms: Monitor received frame 28 with 15920 ms delay.
31702 ms: 1.030 seconds after previous frame, 0.971 FPS.
32732 ms: Monitor received frame 29 with 15920 ms delay.
32732 ms: 1.030 seconds after previous frame, 0.971 FPS.
33762 ms: Monitor received frame 30 with 15920 ms delay.
33762 ms: Monitor exits simulation.
```

Project Assignment 8

- Task: Pipelining and parallelization of the DUT module
  - Expected simulated performance values (in **`Canny.txt`**):

Model	Frame Delay	Throughput	Total
CannyA8_step1	0 ms		0 ms
CannyA8_step2	15860 ms		59320 ms
CannyA8_step3	15860 ms	0.549 FPS	59320 ms
CannyA8_step4	15860 ms	0.549 FPS	59320 ms
CannyA8_step5	15920 ms	0.971 FPS	33762 ms

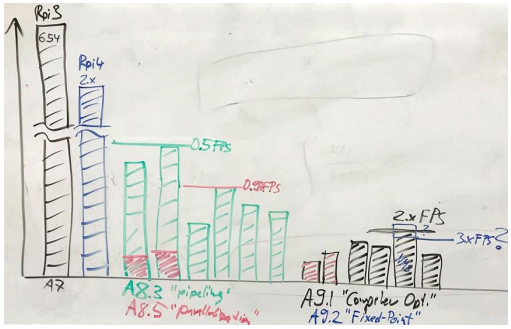
(values based on Raspberry Pi 3 measurements)

Project Assignment 9

- Task: Throughput optimization by pipeline load balancing
  - Optimize the bottleneck stages to improve throughput
- Steps
  1. Apply compiler optimizations for maximum execution speed
     - Try GNU compiler options `-O2`, `-O3`, and others
     - Back-annotate the best performance you can find
  2. Consider fixed-point instead of floating-point arithmetic
     - Use fixed-point arithmetic in NMS module
     - Evaluate the trade-off between speed and accuracy
- Deliverables
  - **`Canny.cpp`** (final SystemC model with best performance)
  - **`Canny.txt`** (performance table, design decisions, reasoning)
- Due
  - Wednesday, December 4, 2019, 6pm

Project Assignment 9

- Step 1: Apply compiler optimizations to improve throughput
  - Try GNU compiler options
    - -O2, -O3, and others
  - Back-annotate the best performance you can find
    - Improvement will be different for different modules



Project Assignment 9

- Step 2: Consider fixed-point calculations instead of floating-point arithmetic
  - Focus on **`Non_Max_Supp`** module only
  - Convert **`float`** type variables to **`int`** types
  - Replace these lines of code…

```
xperp = -(gx = *gxptr)/((float)m00);
yperp = (gy = *gyptr)/((float)m00);
```

  - … with this code

```
gx = *gxptr;
gy = *gyptr;
xperp = -(gx<<16)/m00;
yperp = (gy<<16)/m00
```

  - Measure the timing difference on the prototyping board
  - Measure and evaluate the image quality (**`ImageDiff`**)