

# Lecture 1

## Embedded system design

### Introduction

*CS476 - ESD*  
*February 18, 2025*

Motivation

Hw/Sw partitioning

Design example

Hardware

Software

Dr. Theo Kluter  
EPFL

Motivation

Hw/Sw partitioning

Design example

Hardware

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- ▶ The first 9 weeks of the semester: theory and practical works (PWs) from which 3 are graded.
- ▶ The last 5 weeks of the semester: Realization of a project in groups of 2 students (either proposed by students or chosen from a list) with a final report.
- ▶ After the semester: presentations and demo of the project.

# Course build-up and grading

- ▶ The first 9 weeks of the semester: theory and practical works (PWs) from which 3 are graded.
- ▶ The last 5 weeks of the semester: Realization of a project in groups of 2 students (either proposed by students or chosen from a list) with a final report.
- ▶ After the semester: presentations and demo of the project.
- ▶ The grading scheme is:
  - ▶ 1st graded PW: 15%
  - ▶ 2nd graded PW: 17.5%
  - ▶ 3rd graded PW: 17.5%
  - ▶ Final project: 50%, with following weights:
    - ▶ Demo: 10%
    - ▶ Presentation: 10%
    - ▶ Report: 20%
    - ▶ Technical contents (methods used): 40%
    - ▶ Quality/organization: 20%
  - ▶ Grade =  $1 + \text{round}(\text{result\_in\_ \% } * 5 * 4)/4$
  - ▶ **Important:** For all parts it should be mentioned who of the two students in the group is the author! This to make individual grading possible.
  - ▶ **Note:** It is not a requirement that the groups are fixed for all graded parts. It is however important for each graded part to note the name and gaspar number of the group members in the report.

- ▶ There is no formal definition of an *embedded system*, but it is generally accepted that:

An embedded system is a type of computer designed  
**to solve a specific problem or task**

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- ▶ *Embedded system software* ranges from a small executive to a large **real-time operating system (RTOS)** with a graphical user interface (GUI).
- ▶ Typically, the embedded system software must **respond to events** in a **deterministic way** and should be guaranteed **not to crash**.

The embedded system landscape is as diverse as the world's population:

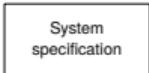
→ **no two systems are the same** ←

Embedded systems range from large computers such as an air traffic control system to small computers such as a handheld computer that fits into your pocket.

Jason Andrews

But how to design an embedded system?

The classic method is the so called waterfall model:



Motivation

Hw/Sw partitioning

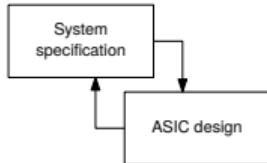
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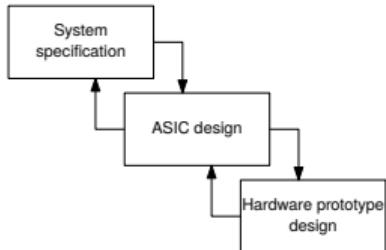
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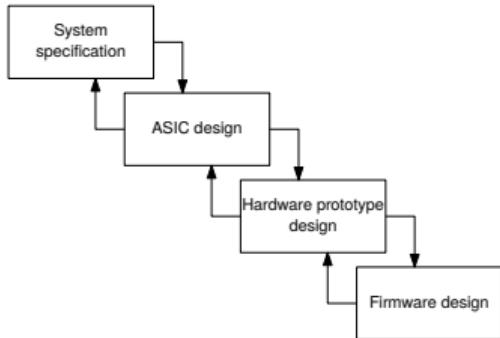
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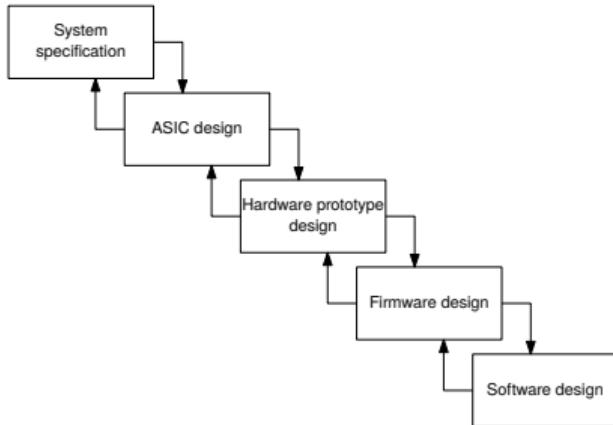
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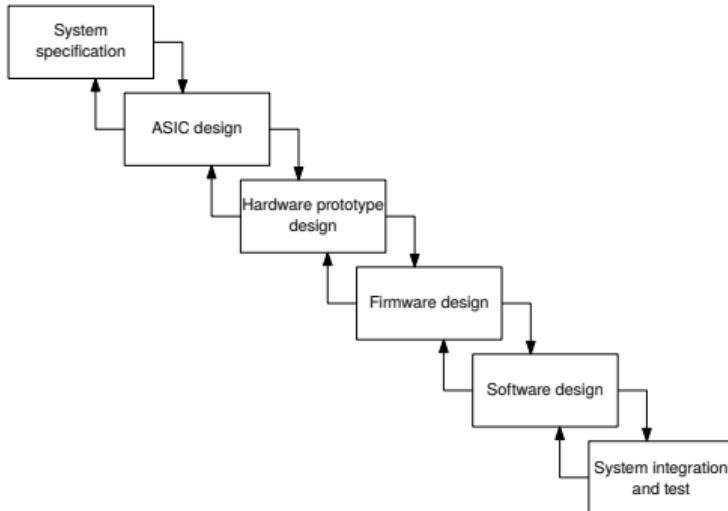
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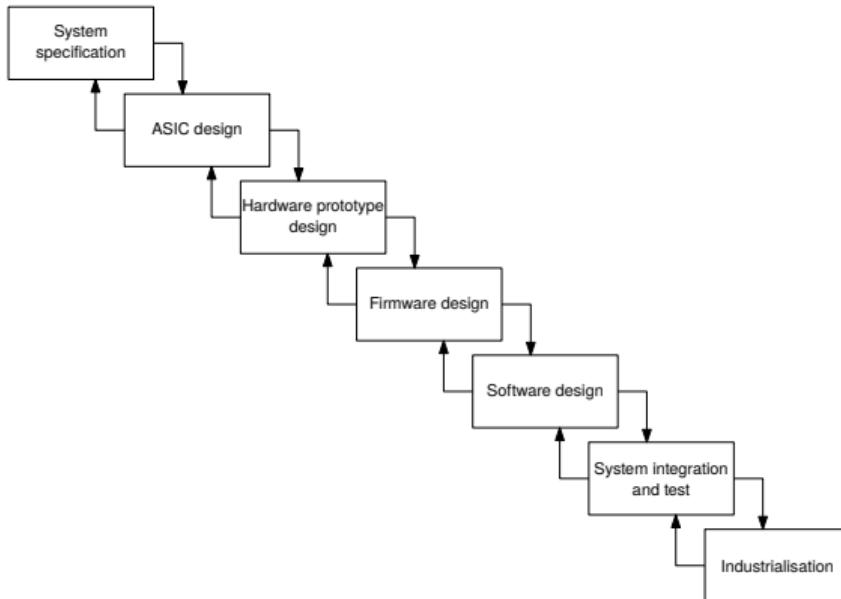
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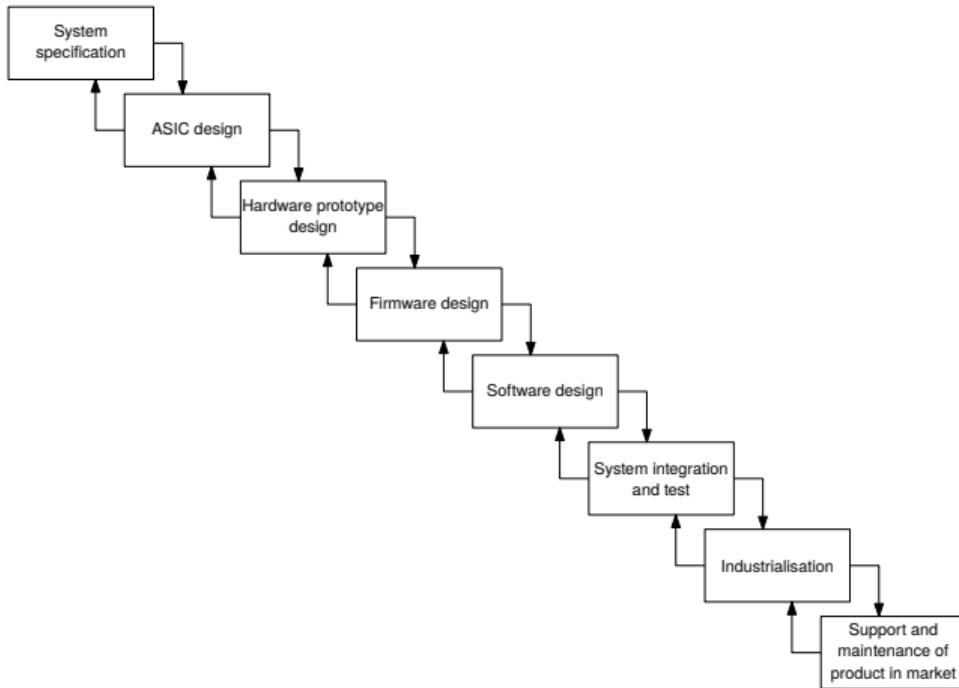
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## How to design an embedded system

With the strict *time-to-market* constraints the classic model does not work, and we need a new method, the *hardware/software co-design* model:

System specification

Motivation

Hw/Sw partitioning

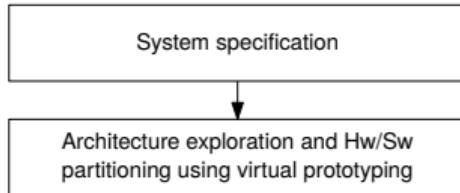
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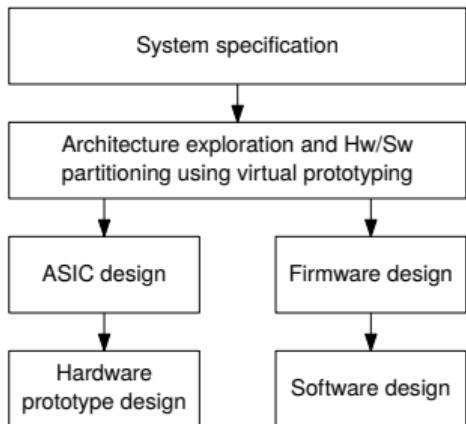
Design example

Hardware

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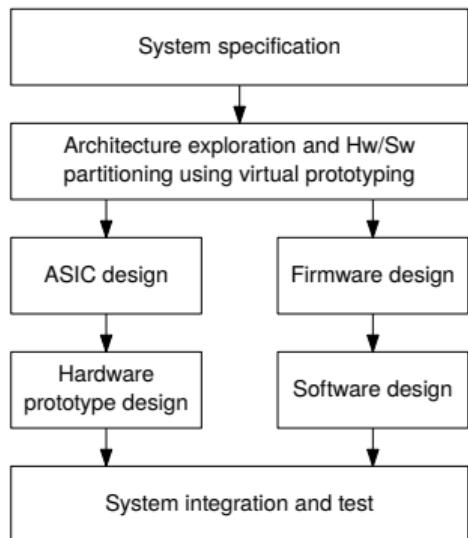
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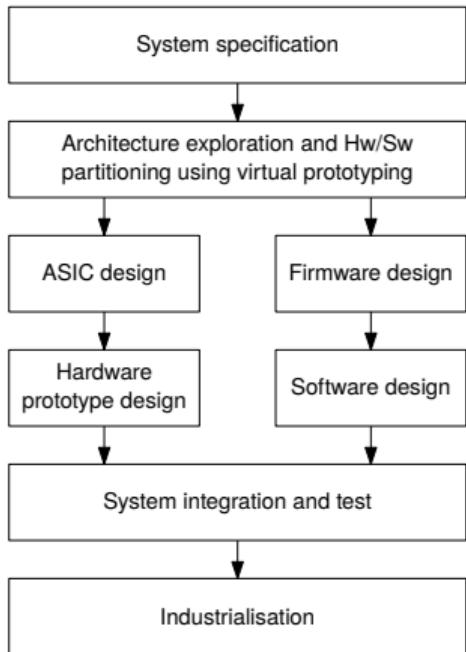
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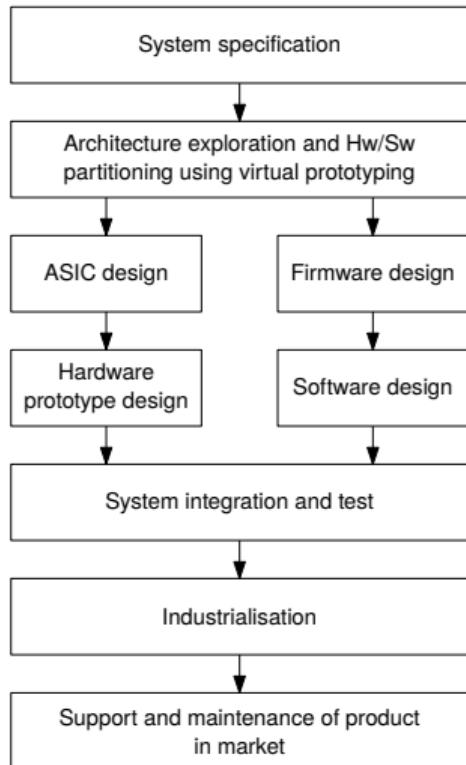
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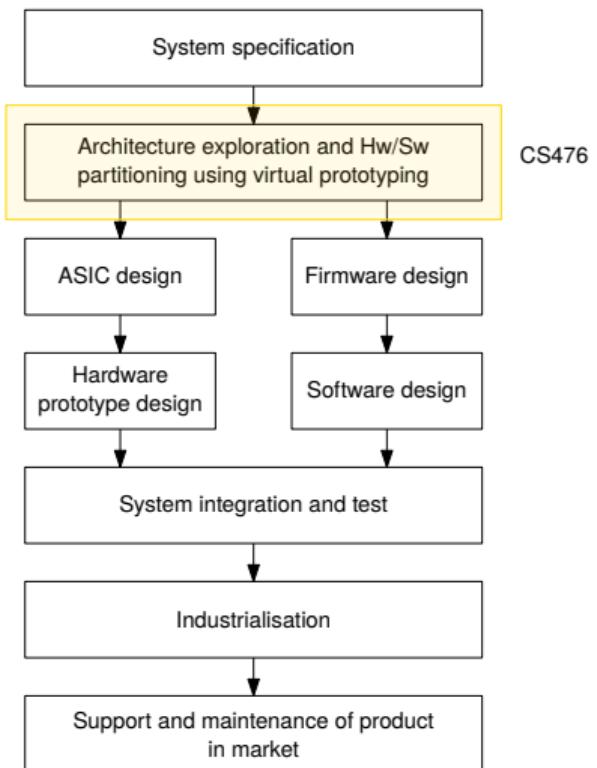
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## Virtual prototype

The *hardware/software co-design* model is based on a virtual prototype. A virtual prototype (VP) is a system that emulates the complete system on a functional level (not necessary cycle-true).

Most requirements are met by a “simple” virtual prototype; system requirements dictate which level of accuracy is required (imposing extra time needed to make the virtual prototype and the time gained afterwards).

How to make a Virtual Prototype?

There are many possibilities:

- ▶ QEMU
- ▶ VHDL/Verilog
- ▶ SystemC/SystemVerilog
- ▶ C/C++
- ▶ MATLAB/Python
- ▶ Java
- ▶ FPGA
- ▶ ...

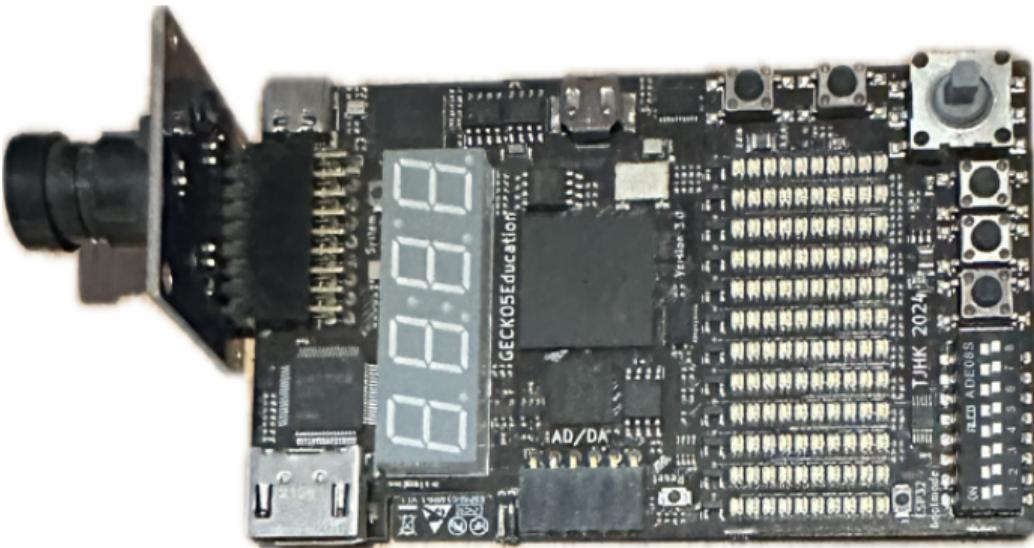
Motivation

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- ▶ In this course we are going to work on a cycle-true virtual prototype (VP).
- ▶ This VP is completely written in Verilog and is running on the GECKO5Education.
- ▶ This VP is completely observable and based on an OpenRISC micro-controller.
- ▶ Note: The OpenRISC micro-controller used is a by BFH developed version for industry projects and is not completely compatible with the one found in the internet.

- ▶ But what are the components that we find in an embedded system?

Motivation

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- ▶ But what are the components that we find in an embedded system?
- ▶ In case of a  $\mu C$  (micro-controller) we find:
  - ▶ Processor(s)
  - ▶ Memory (memories)
  - ▶ Programmable Interface(s)
  - ▶ Sometimes external Address, Data, and Control buses.
  - ▶ Very often Analog components like analog-digital (AD)-converters and digital-analog (DA)-converters.

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- ▶ Some examples for  $\mu C$ -based embedded-systems are:
  - ▶ The Arduino platform based on an Arm® Cortex®-M0 32-bit SAMD21.
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  - ▶ The HiFive Boards platforms based on the RISC-V  $\mu C$ .
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- ▶ The virtual prototype we are going to use also falls in this class of systems:

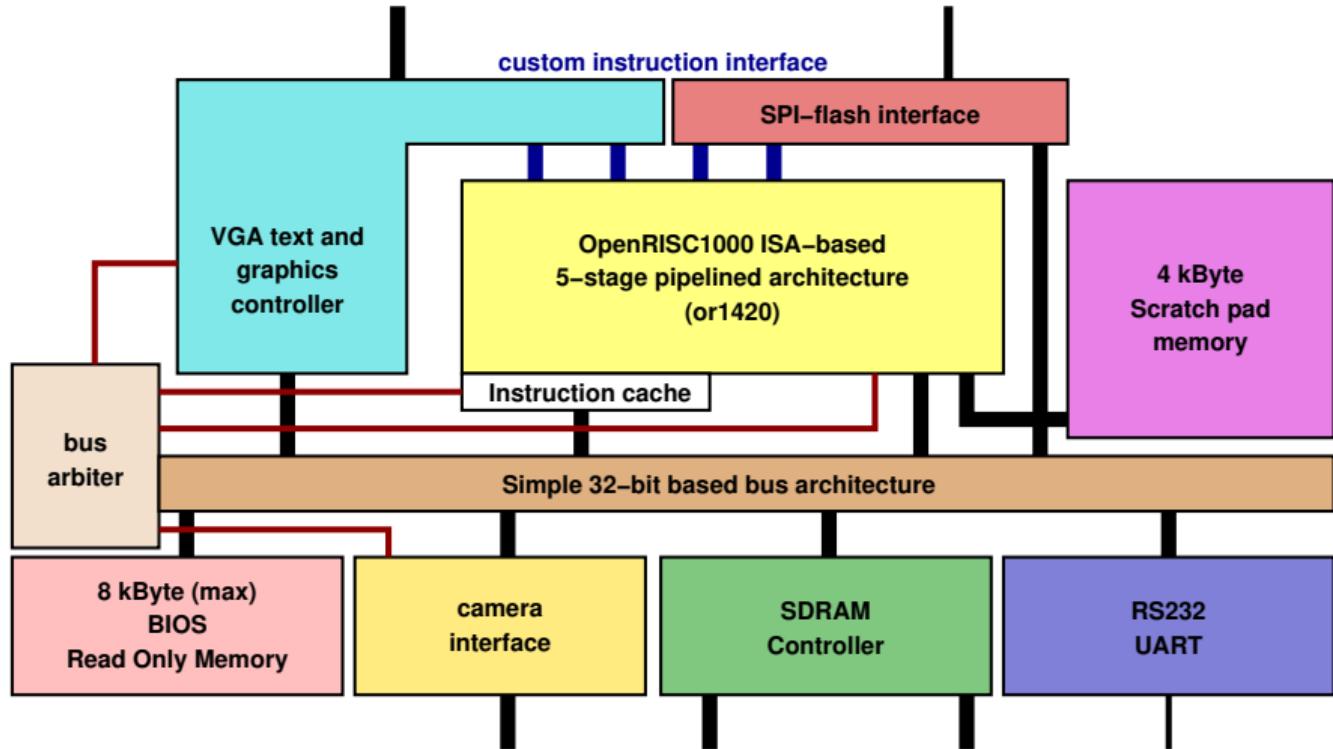
Motivation

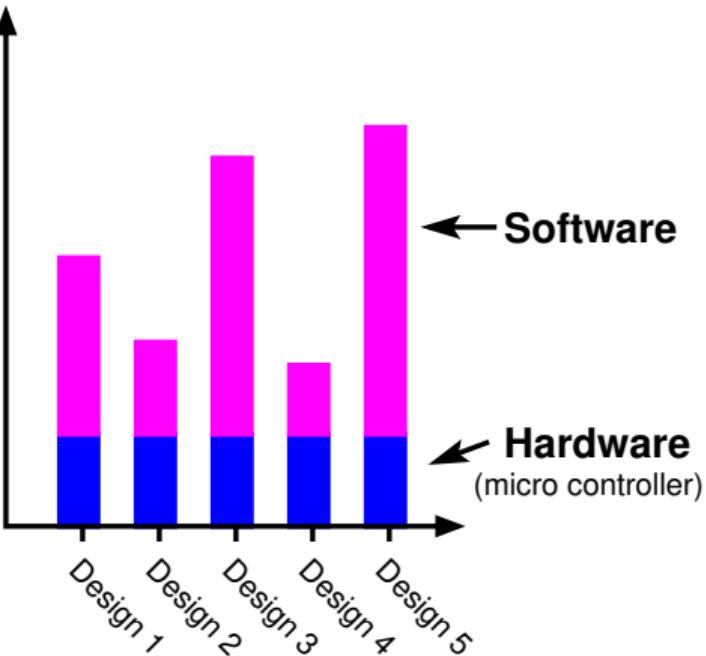
Hw/Sw partitioning

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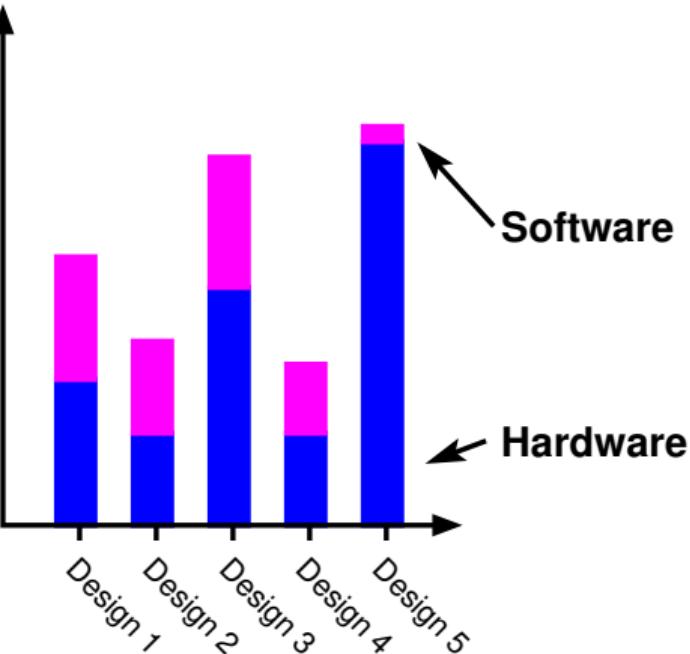
Hardware

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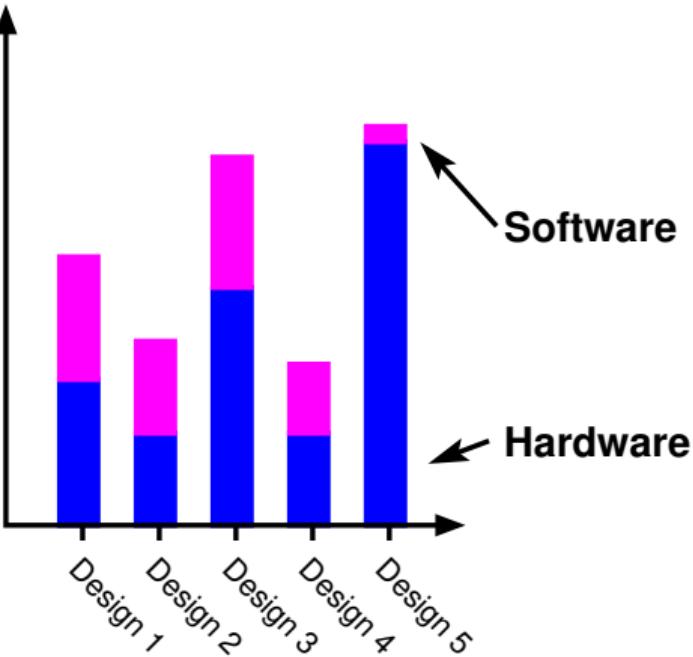




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- ▶ Today, most designs have a varying portion of hardware and software to realize the functionality.
- ▶ But how to partition?

Motivation

Hw/Sw partitioning

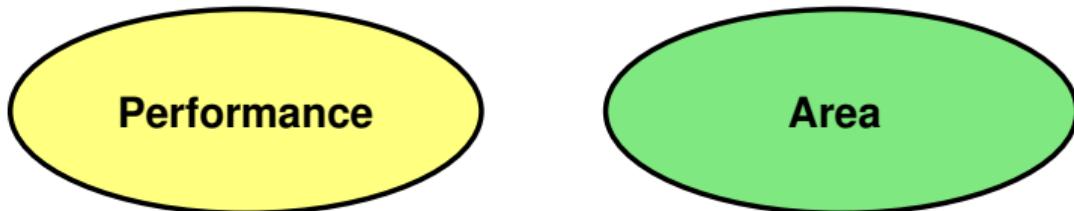
Design example

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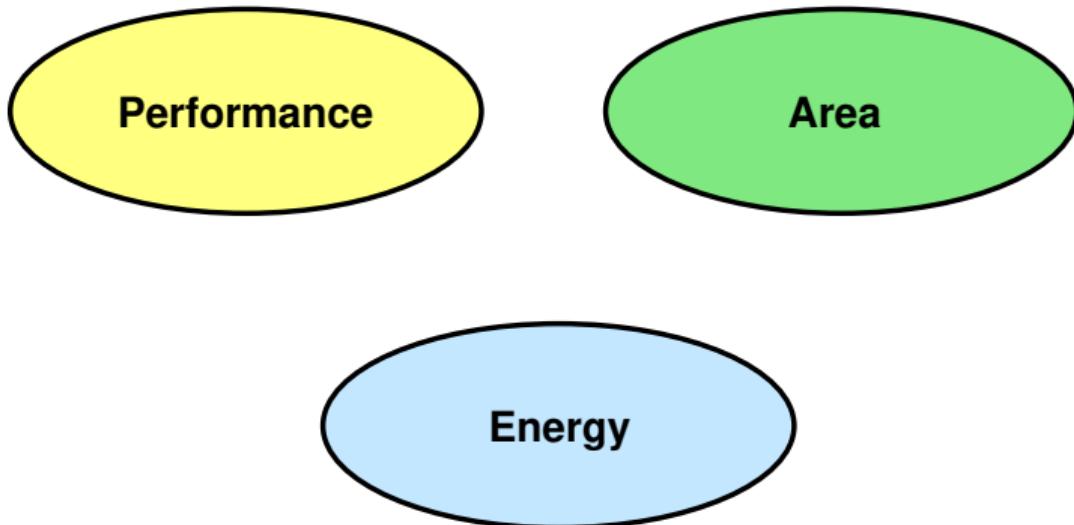
Software



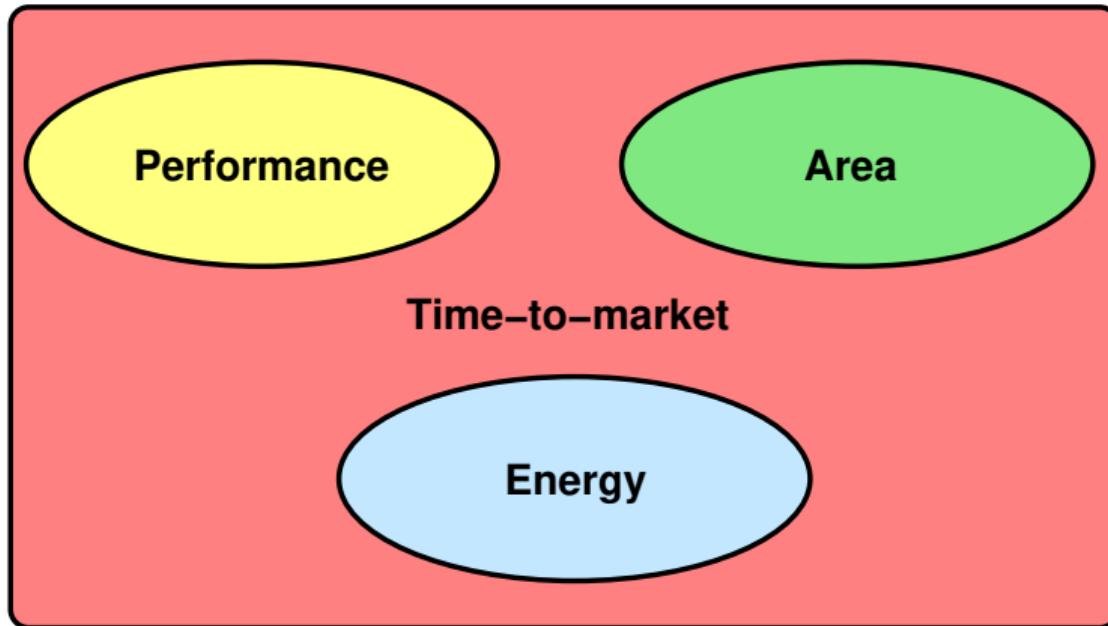
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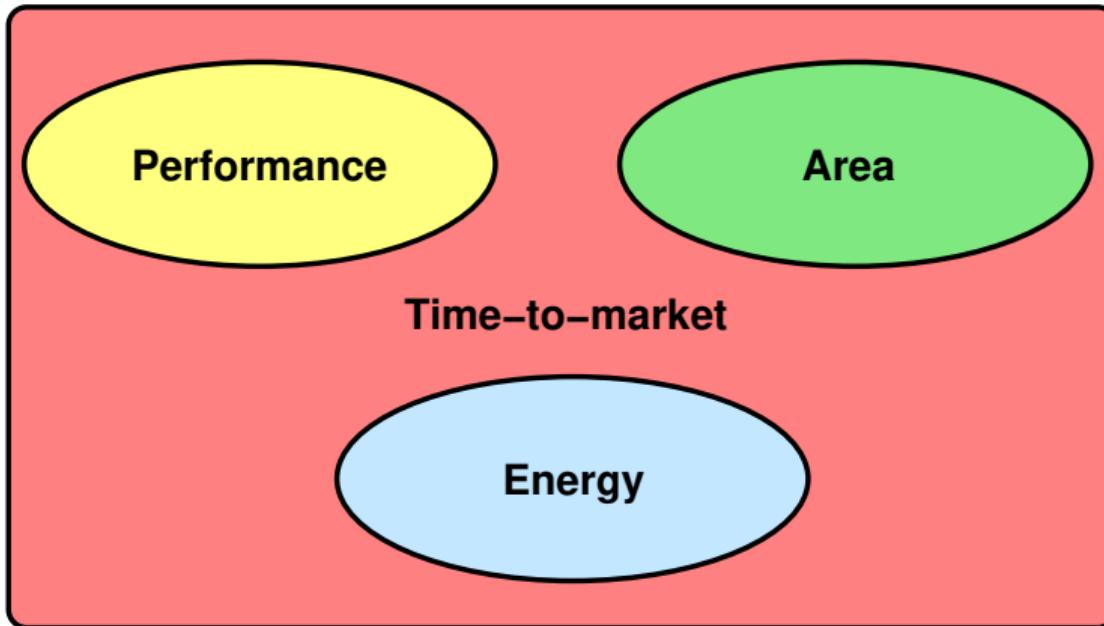
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- ▶ In general it is impossible to meet them all, we have to make trade-offs.
- ▶ Worst even, nowadays **time-to-market** constraints imposes fast design iterations.
- ▶ If we do not appear before the competition the effort is in vane....

Motivation

Hw/Sw partitioning

Design example

Hardware

Software

# So how do we do it?

Motivation

Hw/Sw partitioning

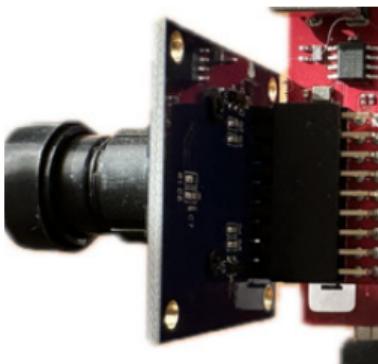
Design example

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# So how do we do it?

Let's take a design example



Motivation

Hw/Sw partitioning

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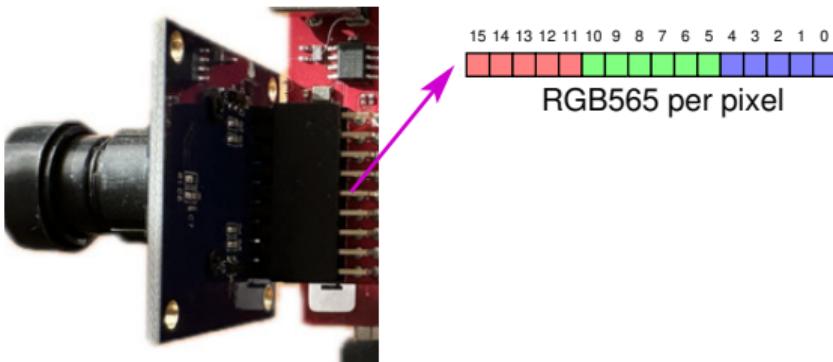
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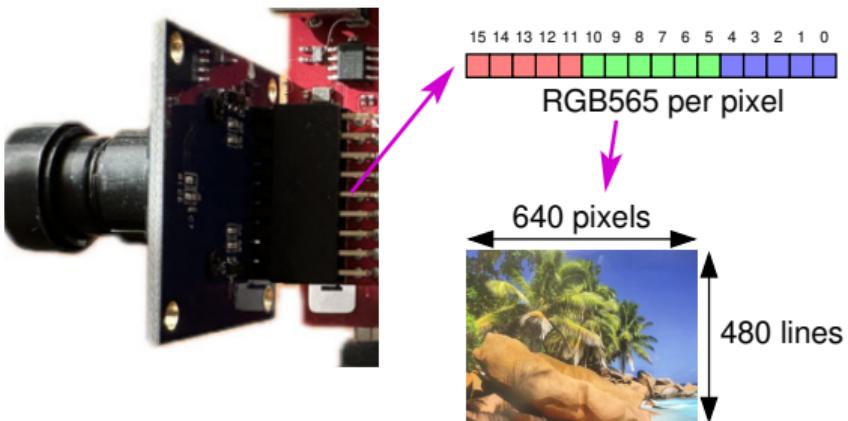
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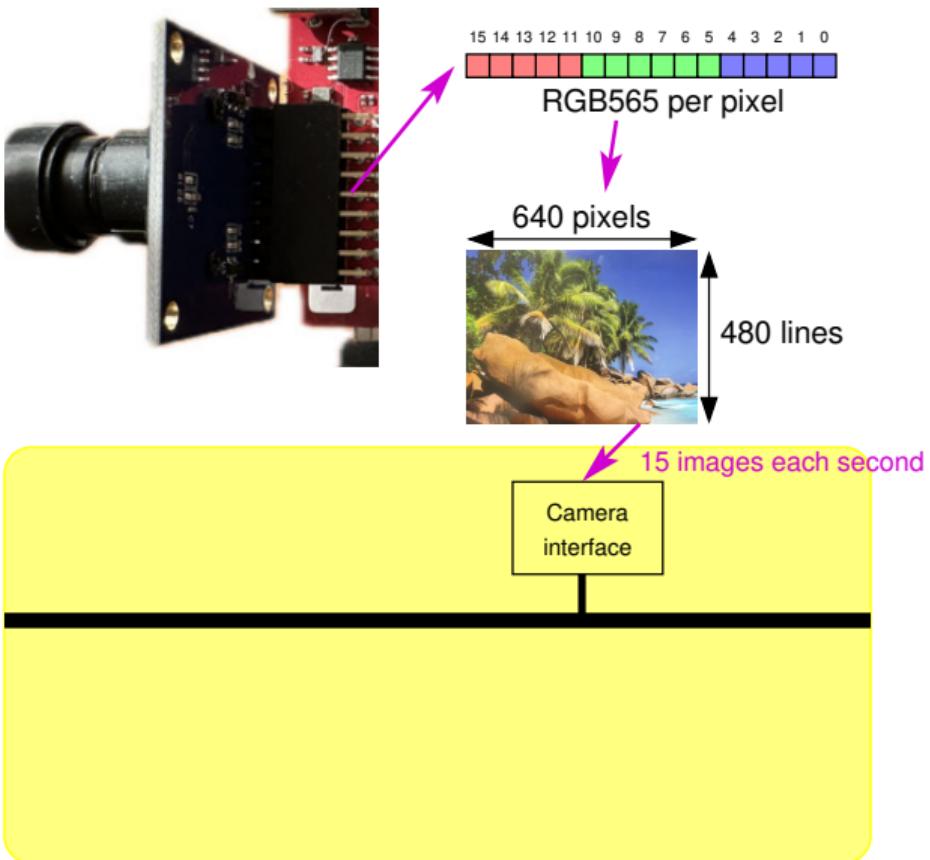
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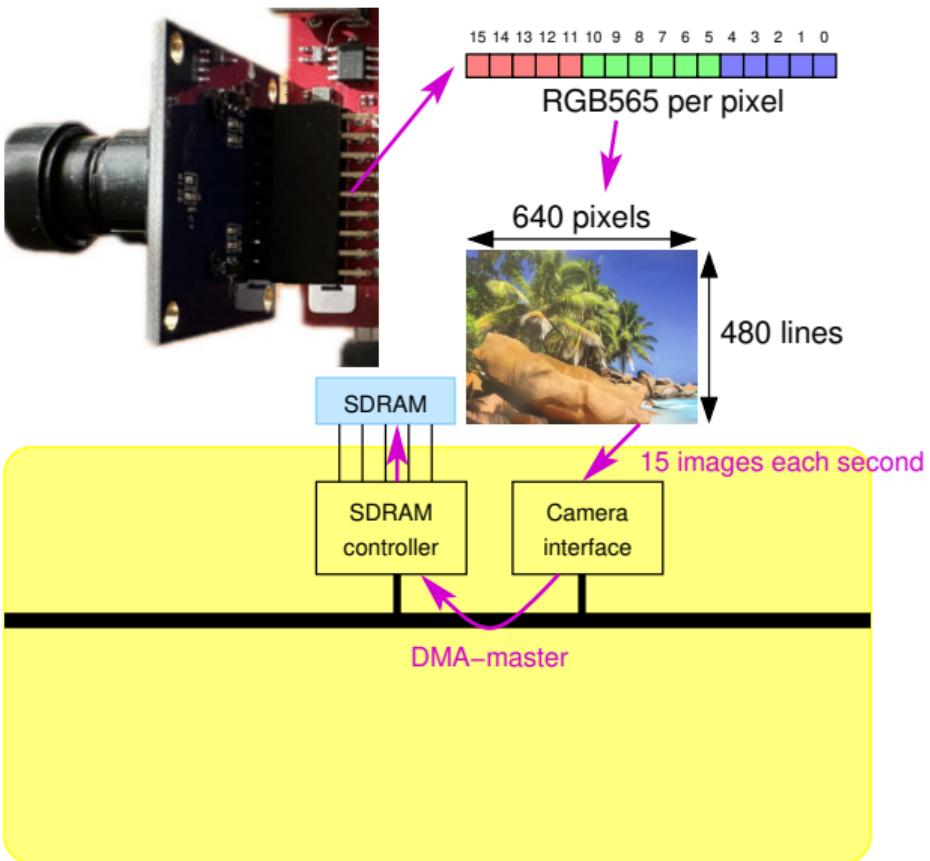
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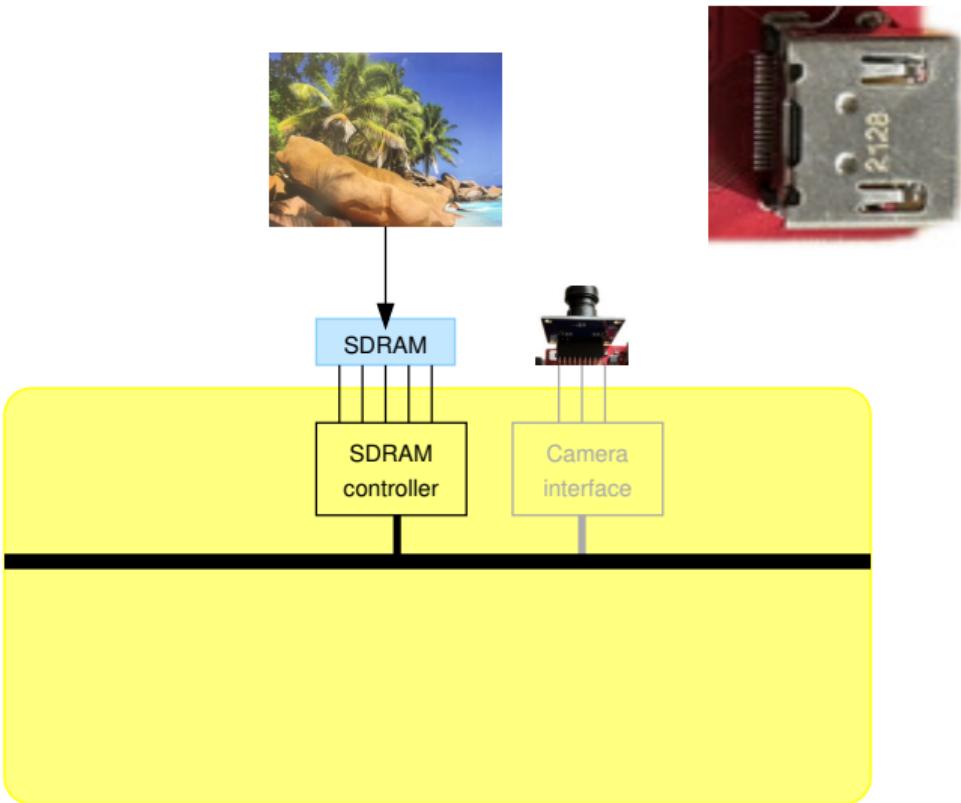
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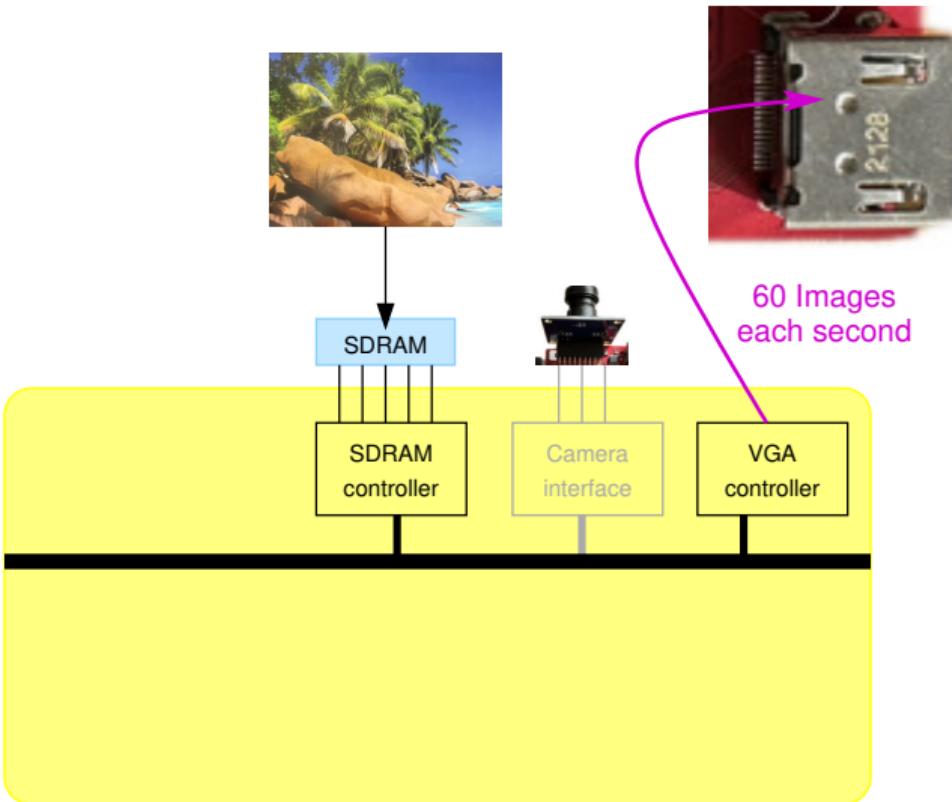
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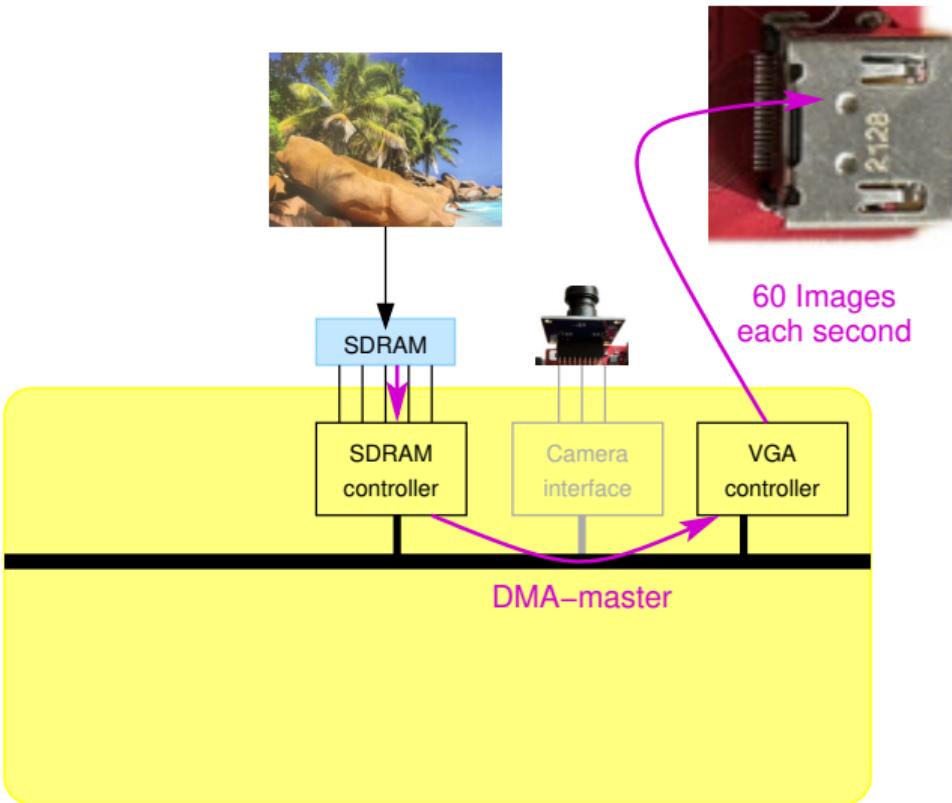
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# DEMO

Motivation

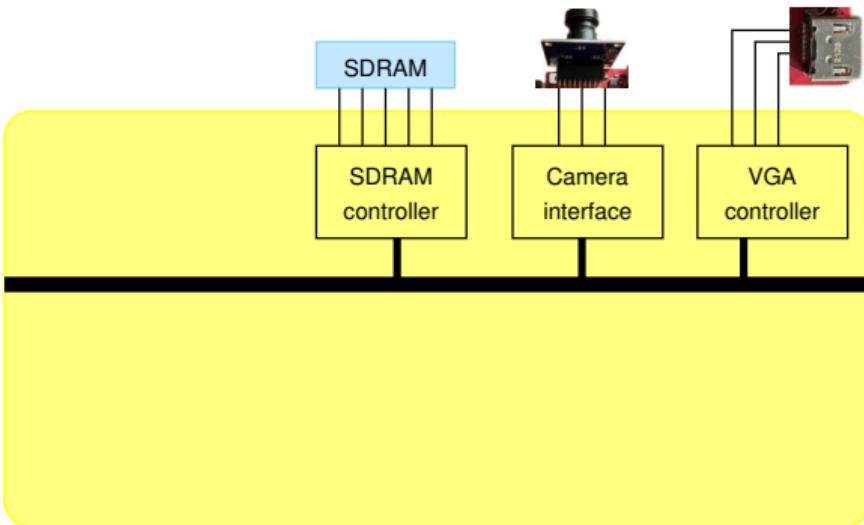
Hw/Sw partitioning

Design example

Hardware

Software

We want to realize an edge-detection  
real-time on the live stream



# Image processing

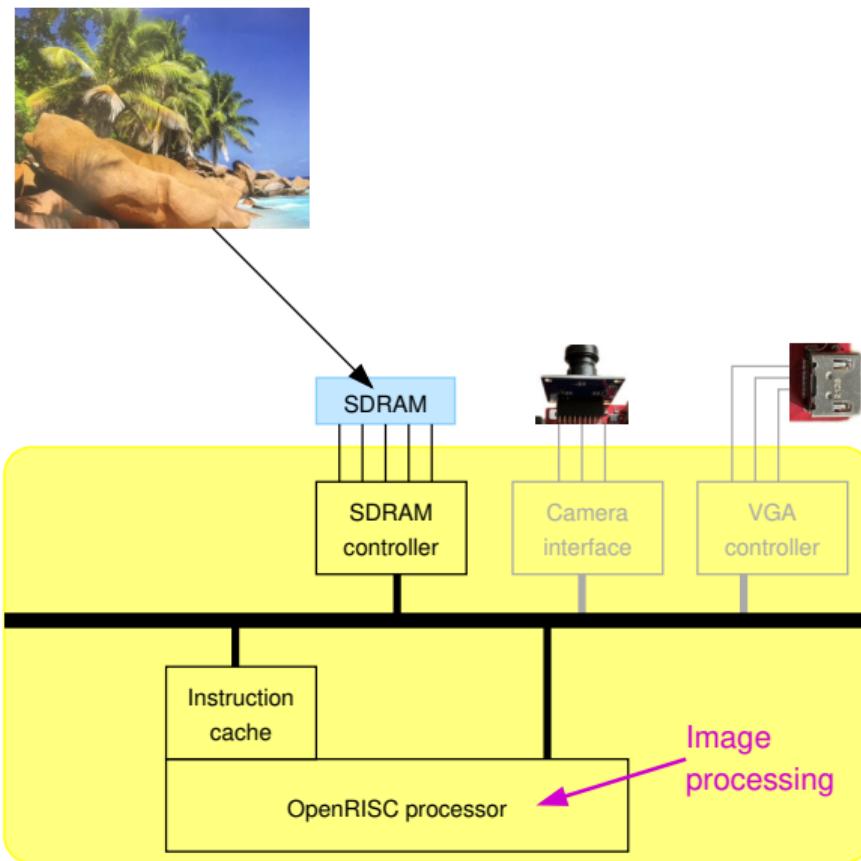
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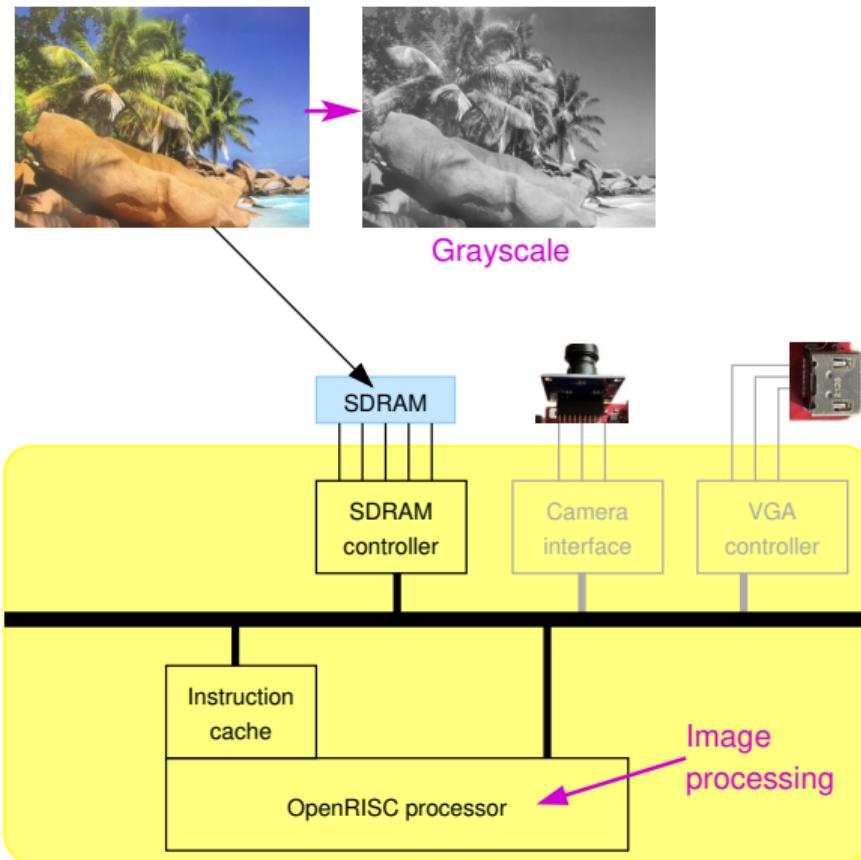
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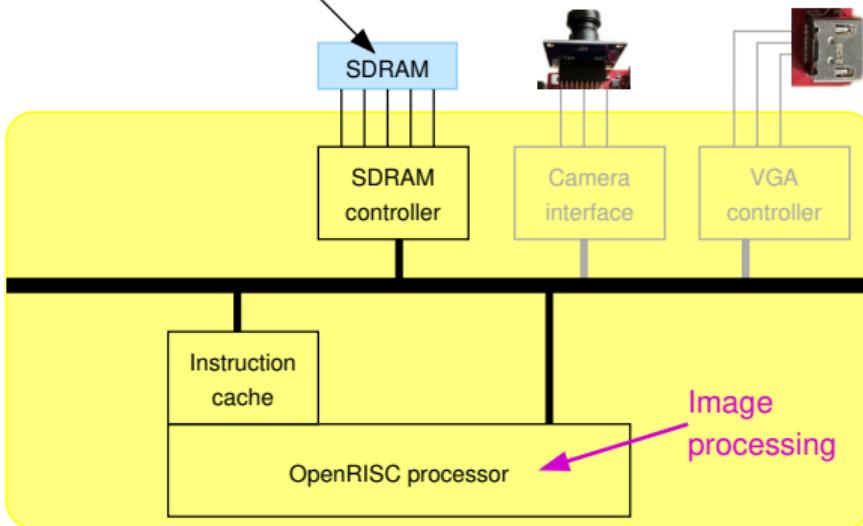
Software

# Image processing



Grayscale

Sobel

Image  
processing

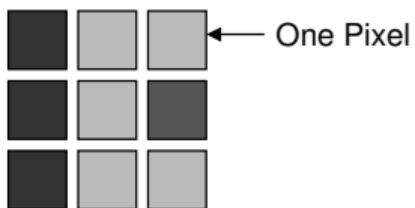
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- ▶ Let's look at a 3x3 pixel array.

# Edge detection (simplified and intuitive)

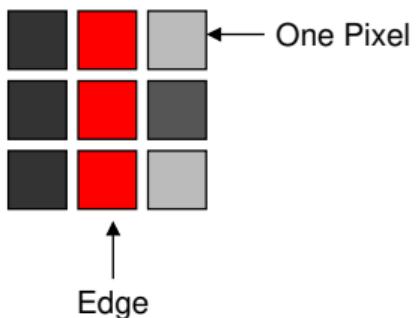
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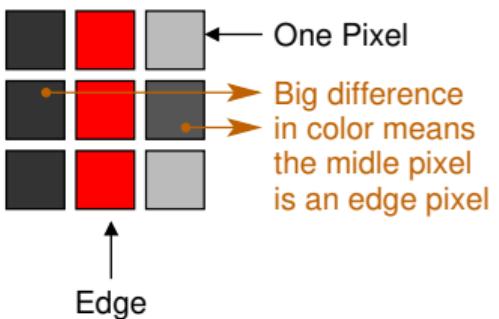
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- ▶ We can also determine the edge by determining the "difference in color" on both sides (left and right) from the edge-pixel.

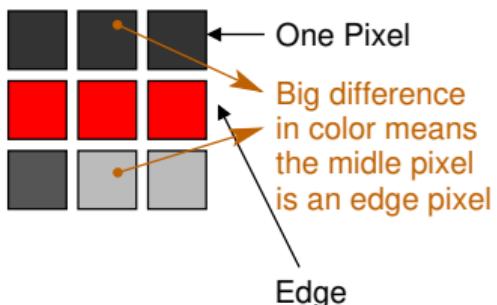
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- ▶ Let's look at a 3x3 pixel array.
- ▶ We can directly see the vertical edge by looking at the colors.
- ▶ We can also determine the edge by determining the "difference in color" on both sides (left and right) from the edge-pixel.
- ▶ To detect horizontal edges we can do the same thing by taking the "difference in color" on both sides (top and bottom) from the edge-pixel.

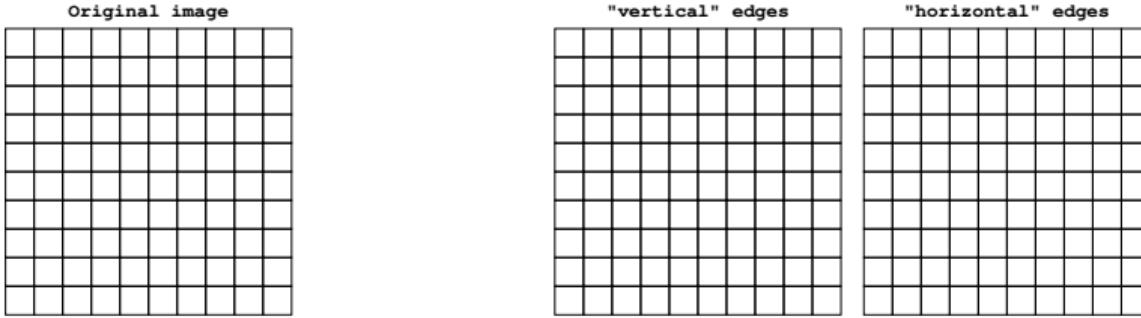
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- ▶ The algorithm of Sobel does something similar.

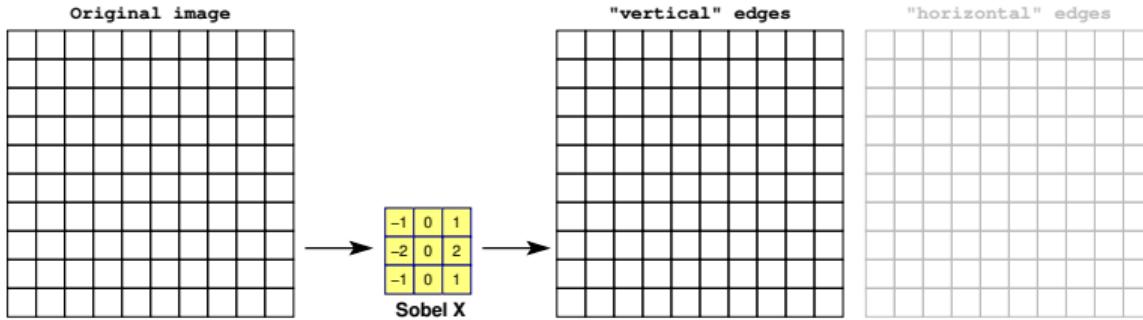
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- ▶ The algorithm of Sobel does something similar.
- ▶ It starts with the “vertical edges” by using a 3x3 X-filter.

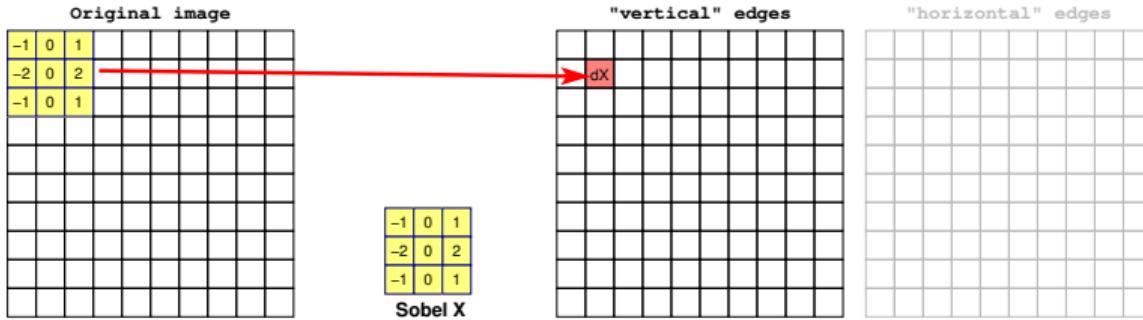
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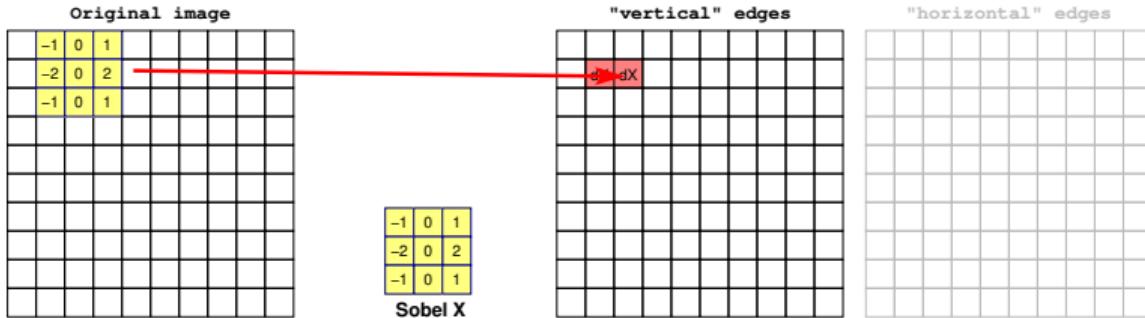
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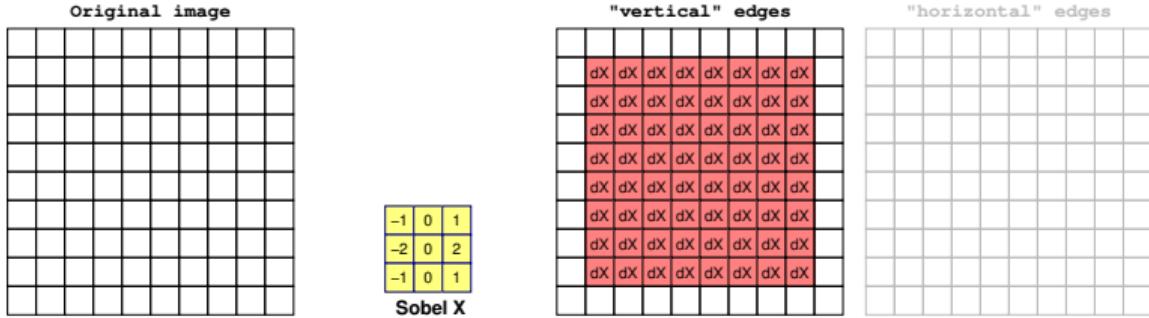
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Hw/Sw partitioning

Design example

Hardware

Software



- ▶ The algorithm of Sobel does something similar.
- ▶ It starts with the “vertical edges” by using a 3x3 X-filter.
- ▶ Each “edge value” is calculated for each pixel.

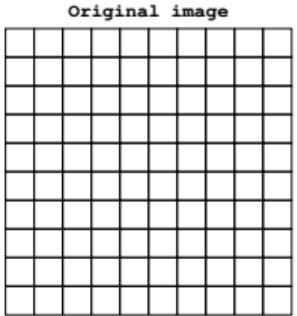
Motivation

Hw/Sw partitioning

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Hardware

Software



"vertical" edges

?	?	?	?	?	?	?	?	?	?
?	dX	?							
?	dX	?							
?	dX	?							
?	dX	?							
?	dX	?							
?	dX	?							
?	dX	?							
?	?	?	?	?	?	?	?	?	?

"horizontal" edges



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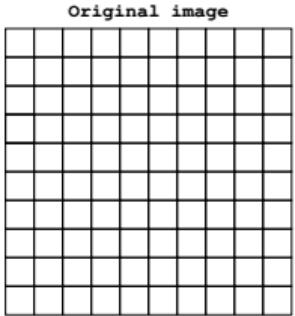
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"vertical" edges

?	?	?	?	?	?	?	?	?
?	$\partial X$	?						
?	$\partial X$	?						
?	$\partial X$	?						
?	$\partial X$	?						
?	$\partial X$	?						
?	$\partial X$	?						
?	$\partial X$	?						
?	?	?	?	?	?	?	?	?

"horizontal" edges

- ▶ Next the "horizontal edges" are determined.

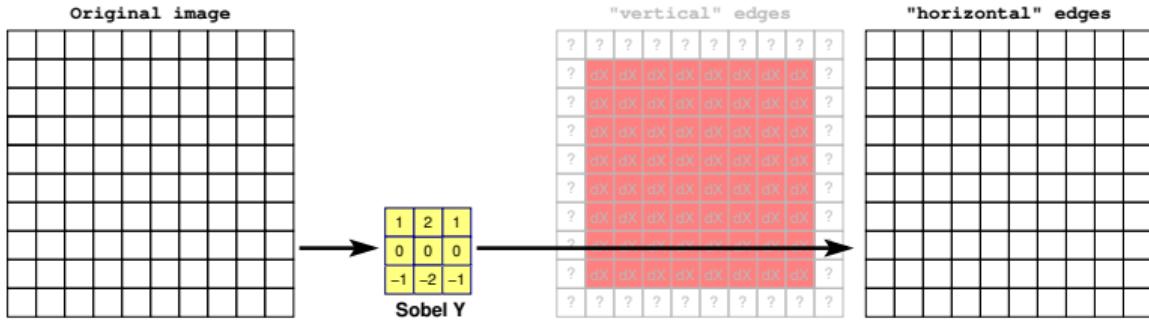
Motivation

Hw/Sw partitioning

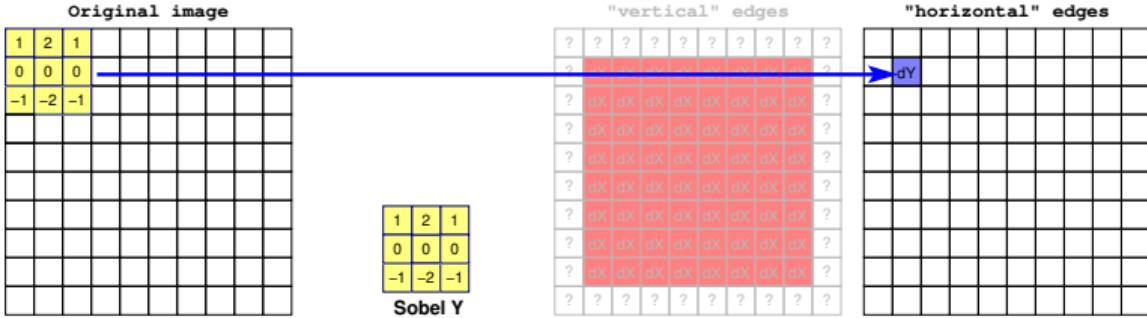
Design example

Hardware

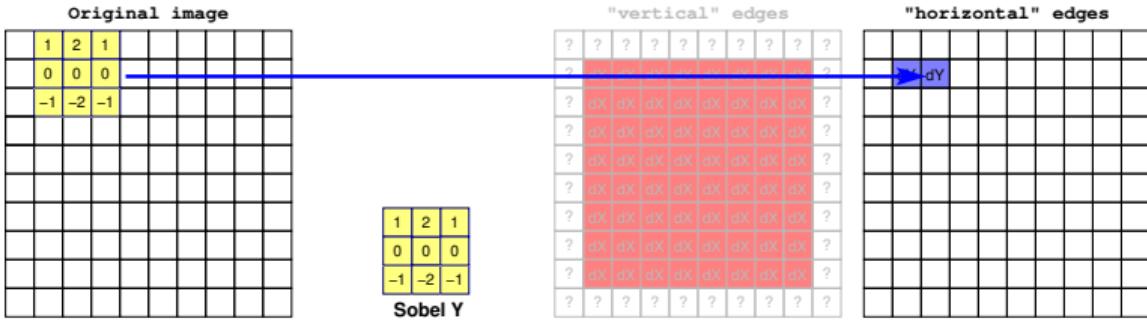
Software



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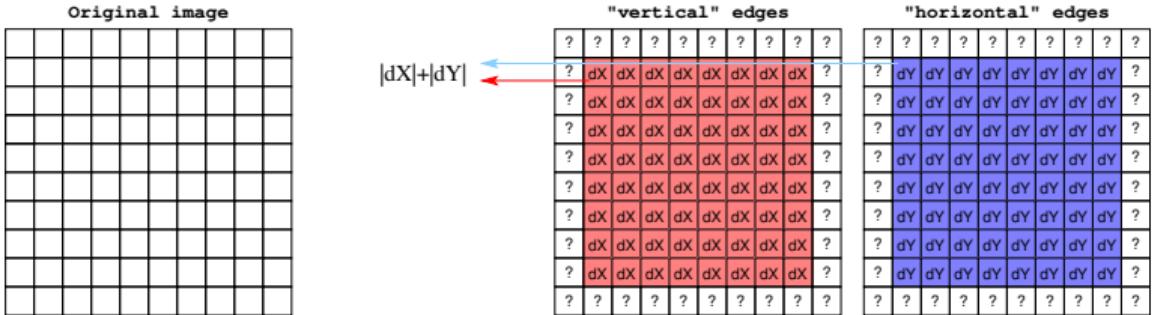
Software

Original image								
?	?	?	?	?	?	?	?	?
?	$dX$	?						
?	$dX$	?						
?	$dX$	?						
?	$dX$	?						
?	$dX$	?						
?	$dX$	?						
?	$dX$	?						
?	?	?	?	?	?	?	?	?

"vertical" edges								
?	?	?	?	?	?	?	?	?
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	?	?	?	?	?	?	?	?

"horizontal" edges								
?	?	?	?	?	?	?	?	?
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	$dY$	?						
?	?	?	?	?	?	?	?	?

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- ▶ Except for the outer pixels!



- Finally the edges are “drawn” by:
- Estimating  $\sqrt{dX^2 + dY^2}$  with  $|dX| + |dY|$

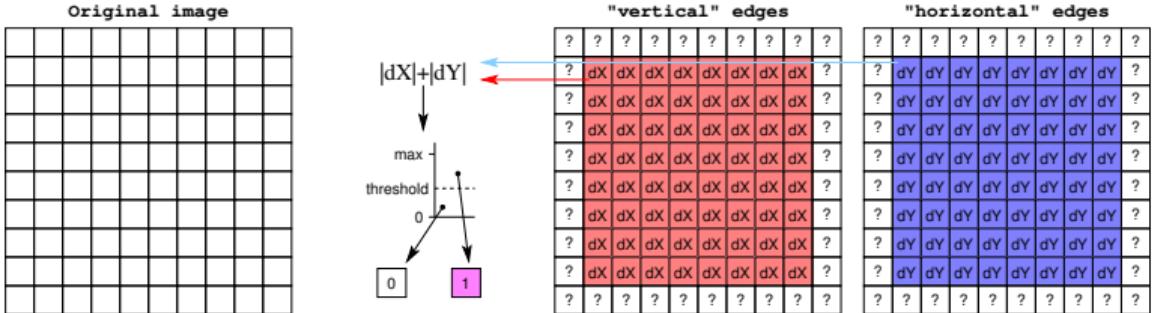
Motivation

Hw/Sw partitioning

Design example

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- ▶ Finally the edges are “drawn” by:
- ▶ Estimating  $\sqrt{dX^2 + dY^2}$  with  $| dX | + | dY |$
- ▶ Doing thresholding of the above value

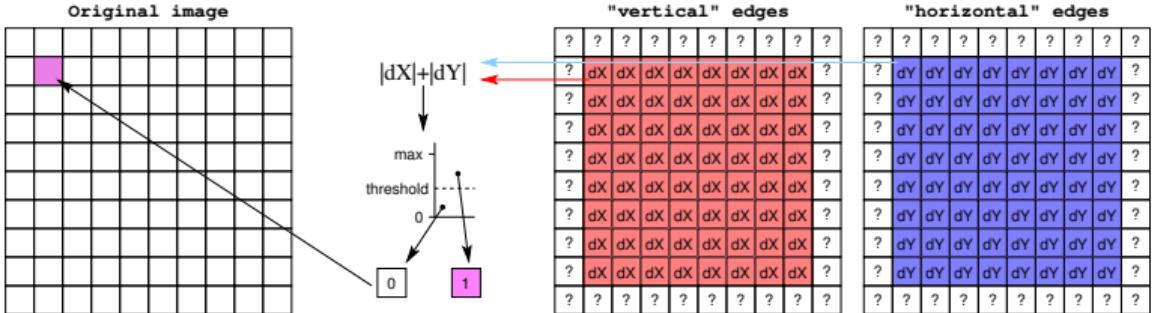
Motivation

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- ▶ Doing thresholding of the above value
- ▶ And draw/clear the pixel

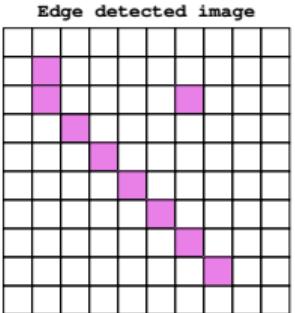
Motivation

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Software



"vertical" edges									"horizontal" edges								
?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	dX	?	?	dY	dY	dY	dY	dY	dY	?							
?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?

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# Putting some numbers

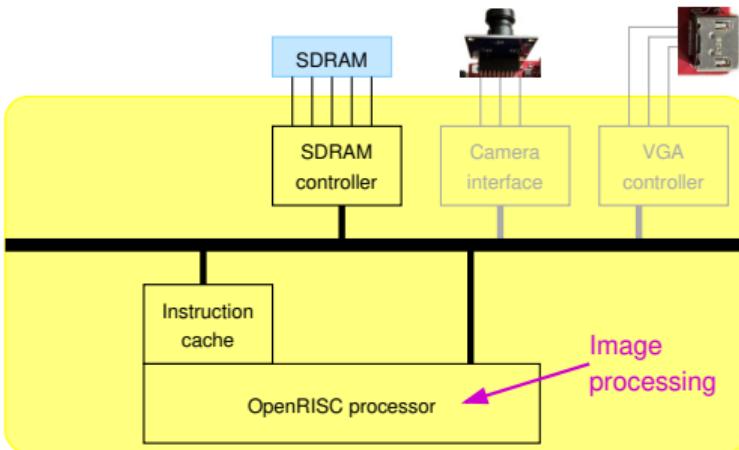
Motivation

Hw/Sw partitioning

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Software



- ▶ Let's put some numbers.

# Putting some numbers

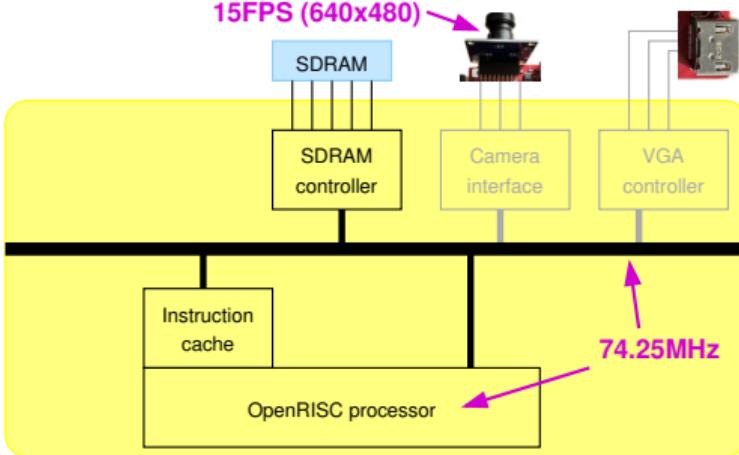
Motivation

Hw/Sw partitioning

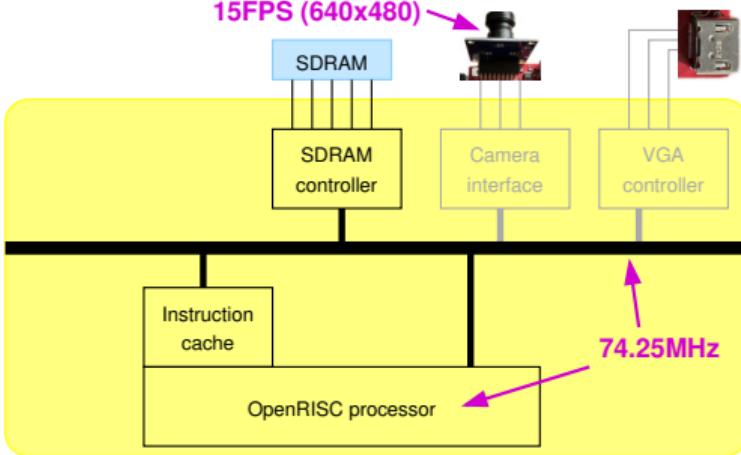
Design example

Hardware

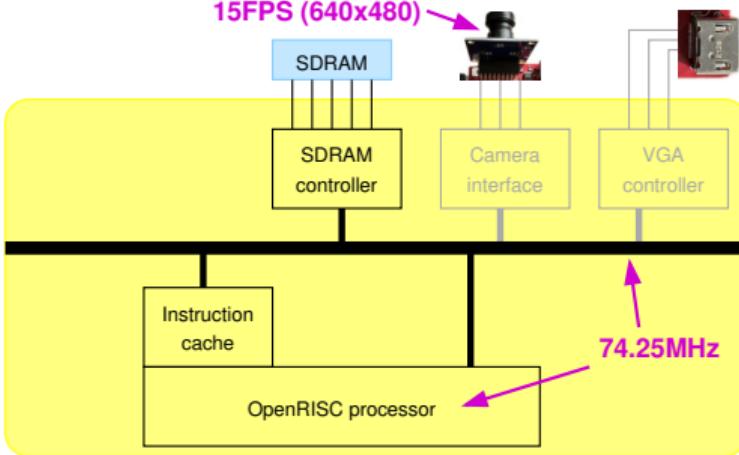
Software



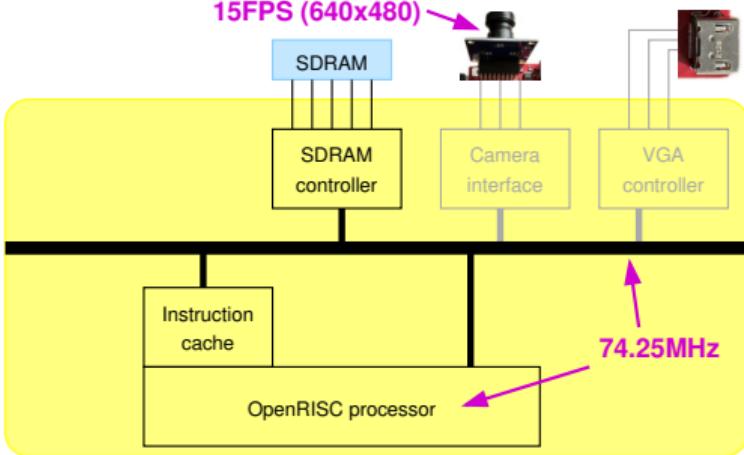
- ▶ Let's put some numbers.
- ▶ Hence we have  $\frac{74.25 \cdot 10^6}{15} = 4.95 \cdot 10^6 \frac{\text{cpu cycles}}{\text{image}}$  or  $\frac{4.95 \cdot 10^6}{640 \cdot 480} \approx 16 \frac{\text{cpu cycles}}{\text{pixel}}$



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- ▶ Back-of-the-envelope:  $dX$  and  $dY$  require each 6 multiplications and 6 additions each pixel, the final operation requires 2 `abs()`, 1 addition, 1 subtraction and 1 set; so  $\approx 30 \frac{\text{cpu cycles}}{\text{pixel}}$



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- ▶ Hence we have an impossibility! How to solve this problem, the main topic of this course.

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# DEMO