POLITECNICO MILANO 1863

DIPARTIMENTO DI ELETTRONICA, INFORMAZIONE E BIOINGEGNERIA

Introduction to the course: context, topics, general organization and exam indications

Giacomo Langfelder

MEMS and Microsensors – M.Sc. in Electronics Engineering

Introduction to the course

- Who
- What
- When
- Where
- Why

A warm welcome, folks!

Ready to start?

https://www.sensorlab.deib.polimi.it/Education.php

Who

- Me , Ing. A. Buffoli, C. Padovani, R. Nastri … and you

- Me:
  - Associate Professor since 2018, Assistant Professor since 2010, Professor of *Optoelectronic Systems and digital imaging* (2012-2015), Professor of *MEMS and Microsensors* (2015-…), Professor of *Electronics* (2020-…)
  - Research interests
    - Digital imaging sensors and related electronics
    - Microelectromechanical systems and related electronics

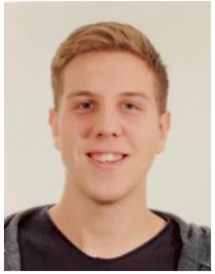
  - giacomo.langfelder@polimi.it
  - Ed. 24 – via Golgi 40, 3rd floor
  - Phone -3425

Please use the keyword: **MMXX** **(stands for MEMS and Microsensors stuff)**

in the *object* of your email. This increases the success rate of your questions to be quickly answered.
This is also the **general password of the course**.

Who

- Your laboratory assistants:
  - Ing. Riccardo Nastri (riccardo.nastri@polimi.it)
    - M.S. Thesis 2021-2022
      - M.S. Thesis on MEMS-based accelerometers
    - Research assistant since June 2022
      - research in the field of MEMS angle gyroscopes
    - Previous teaching assistant for *MEMS and Microsensors*



  - Ing. Christian Padovani (christian.padovani@polimi.it)
    - M.S. Thesis 2020-2021
      - M.S. Thesis on integrated circuits for frequency modulated MEMS
    - Ph. D. student since May 2021
      - Ph.D. research in the field of MEMS accelerometers

  - Ing. Andrea Buffoli (andrea.buffoli@polimi.it)
    - M.S. Thesis 2020-2021
      - M.S. Thesis on integrated circuits for NEMS gyroscopes
    - Ph. D. student since May 2021
      - Ph.D. research in the field of M&NEMS gyroscopes

- Ed. 24 – via Golgi 40, 3rd floor Phone -6152 or -3744

Who

- What about you? Last year data
  - ~ 100 new enrolled people, about 15% foreign students
    - expected final new enrollment: similar
    - expected total: ~ 120 (initially in class ~ 70-80)
  - Background
    - Electronics (most of you)
    - Biomedical, (about 15%)
    - Physics (about 4%)
    - Mathematics (about 2%)
    - Other/Erasmus (about 2%)
  - 4th (most) or 5th (20%) year

Introduction to the course

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What: sensors and transducers

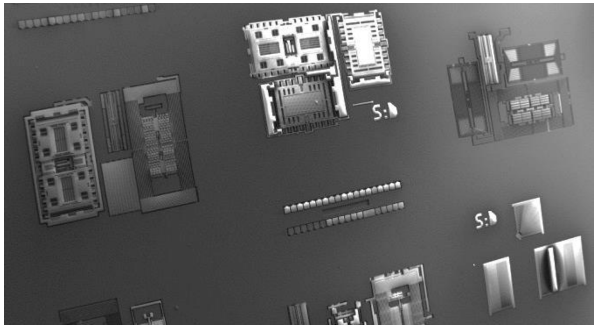
- The course aims at introducing the fundamental concepts of a few kinds of **modern microelectronic devices** (sensors, resonators, transducers) and associated systems, which allow:
  - **acquiring information from the physical world around us**,
  - and **to perform actions on it at the microscopic level**.

- The focus is **centered on MEMS** (microelectromechanical systems) **and CMOS*** (complementary metal-oxide-semiconductor) **technologies**.

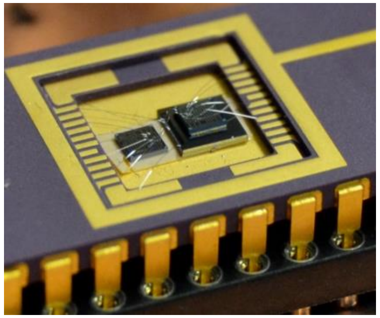
**intended as the same technology of integrated circuit (IC) but here used for sensors!*

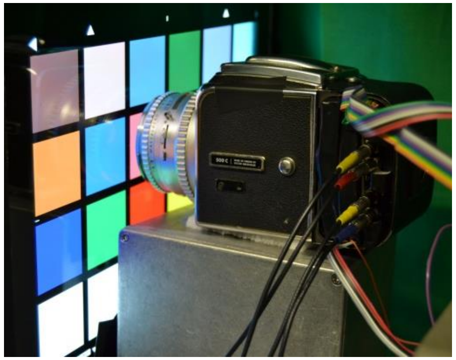
- The **challenge** is common for both the sensor categories: simultaneous **miniaturization**, **performance** improvement and power **consumption** reduction, driven by concepts as *"autonomous car"*, *"sensors ubiquity"*, *"Internet of Things – IoT"* & *"Industry 4.0"*.

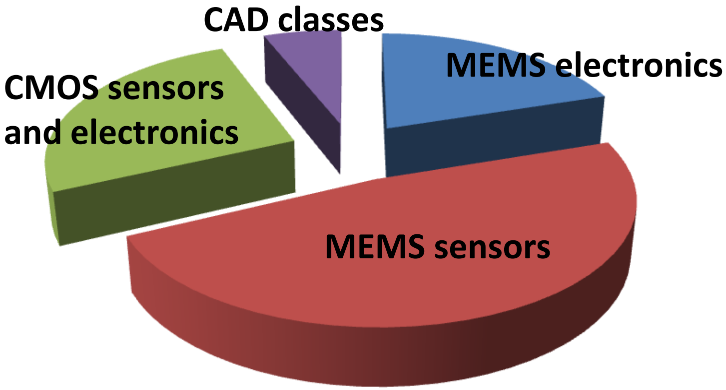
What: the course topics

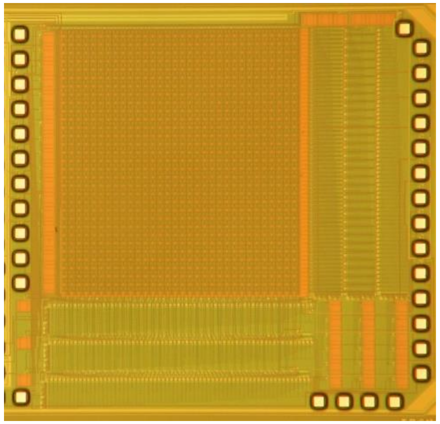


- The course is about
  - **MEMS sensors**
    - inertial, magnetic, resonators
  - MEMS **electronics**
    - capacitive driving and sensing interfaces, oscillators
  - CMOS **optical sensors**
    - device and pixel-level electronics
  - **CAD** classes
    - software



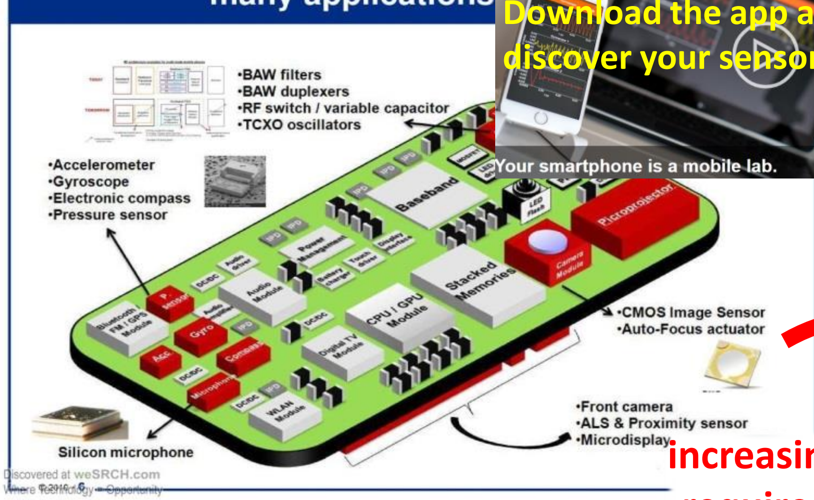


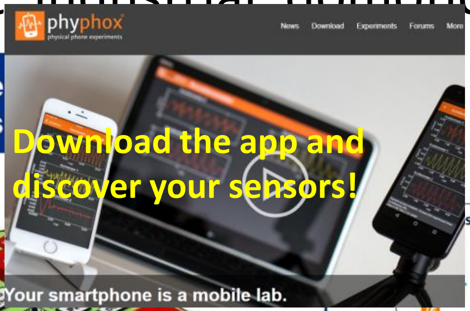


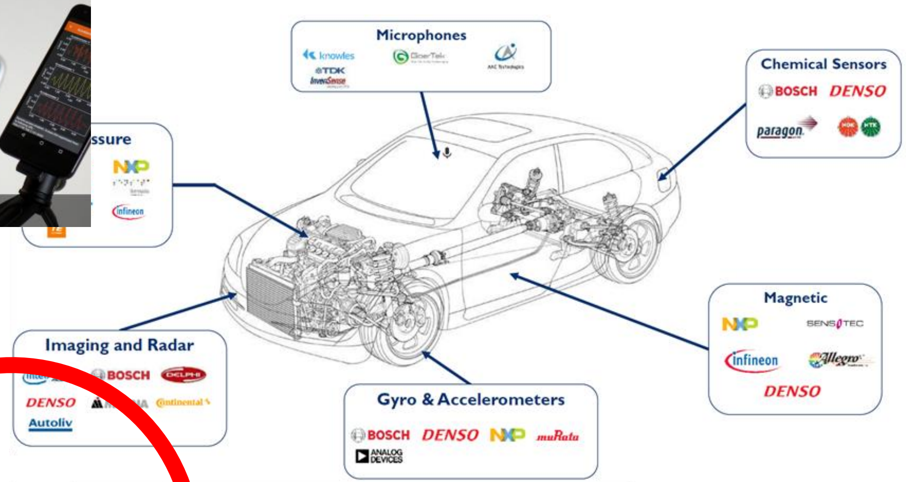


What: MEMS systems applications

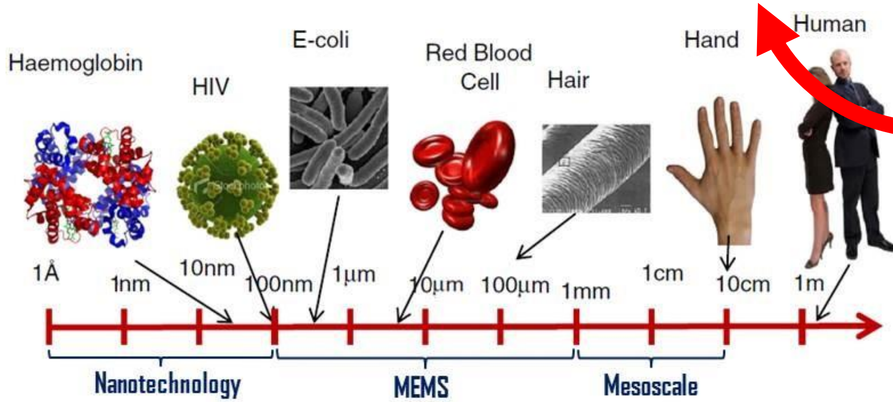
- MEMS is a relatively young technology for sensors and actuators of physical quantities, which is **pervasively invading our everyday life** in consumer, transport, industrial, domotics and medical fields…





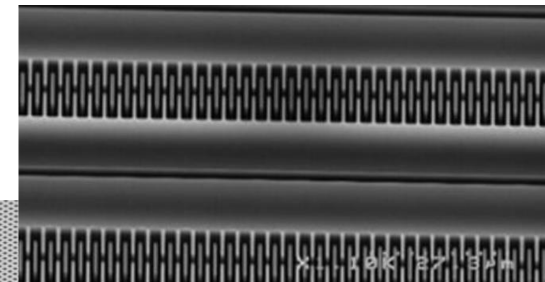


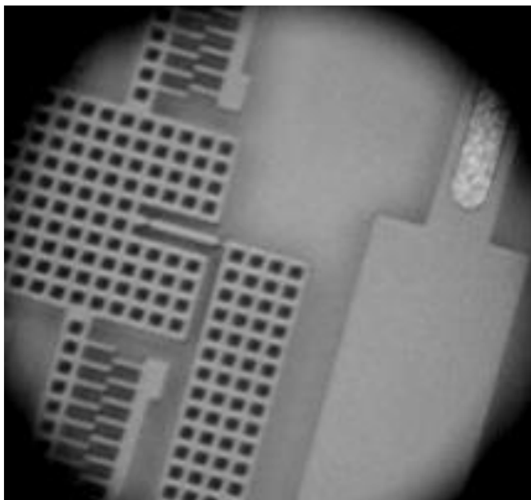
increasing degree of required reliability

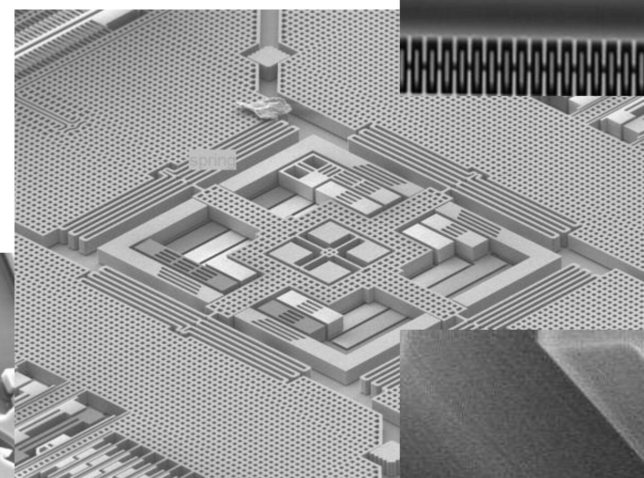


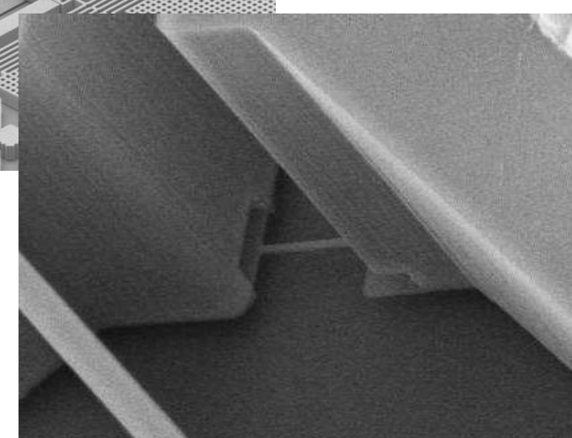
What: machines at the microscale

- MEMS **device size can be as large as 1 mm**, but **characteristic dimensions** (those that determine the performance) can be **as small as 1 μm or even few 100 nm (NEMS)**.





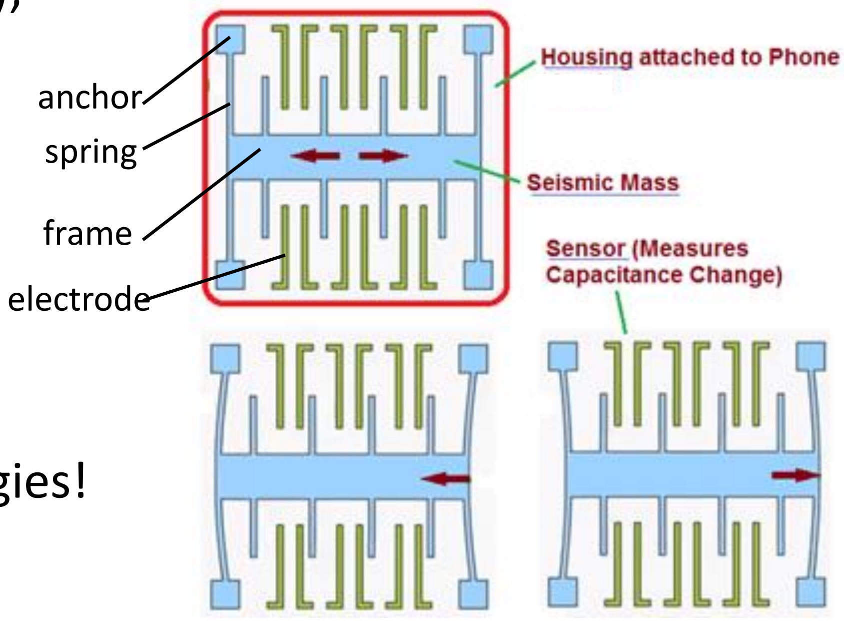




Micro → microtechnology
Electro → electrical interface (capacitive)
Mechanical → microstructures
System → electronics

What: MEMS systems at a glance

- In its simplest form, the MEMS is just a combination of:
  - **Frames suspended through springs** and partially **free to move** under the action of external forces (in light blue);
  - Elements fixed to the substrate to form anchor points or **capacitive readout electrodes**
  - Suitable **housing/packaging**
  - All of this in compact dimensions, designed in microelectronic technologies!

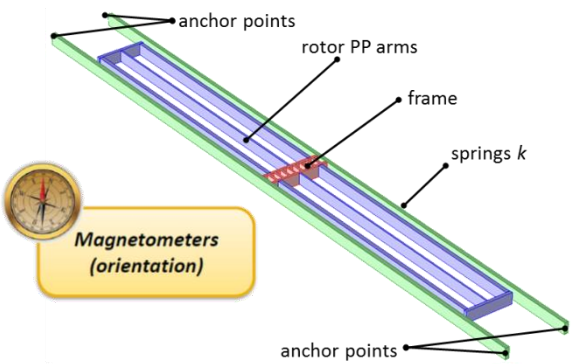


- Working principle of a MEMS sensor:
a force moves the suspended frame, and we detect the motion through suitable electrodes: we can thus **quantify the force that acted on the device** using **smart electronics** for processing.

What: MEMS inertial sensors

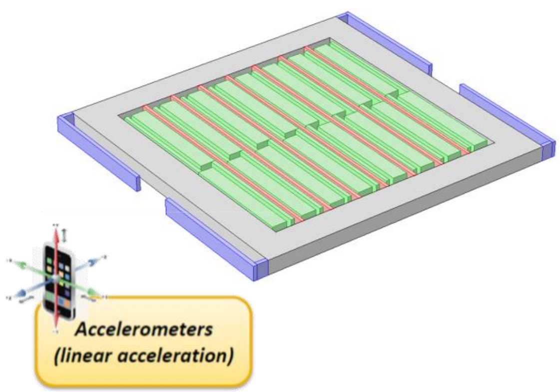
- **Inertial sensors**: measurement of initial orientation and relative motion of a non inertial reference system

***Initial orientation**:*
MEMS magnetometers



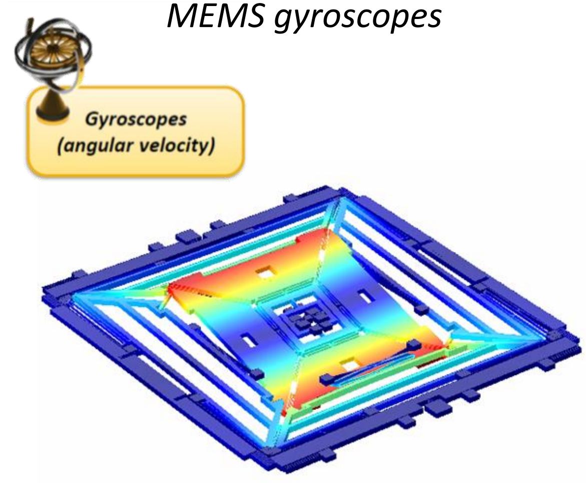
Digital compass
Current sensing
Vehicle monitoring
…

***Linear motion**:*
MEMS accelerometers



Display orientation
Airbag activation
Soil exploration
…

***Rotational motion**:*
MEMS gyroscopes



Gaming
ESC activation
Military trajectory compensation
…

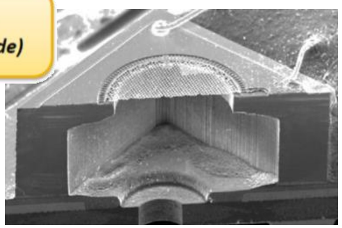
→ Enable inertial navigation in absence of GPS!

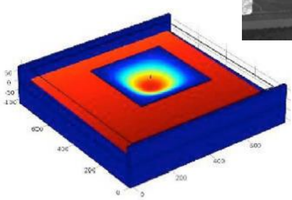
Indoor navigation
Submarine navigation
Non-trackable navigation
Through-skyscrapers navigation

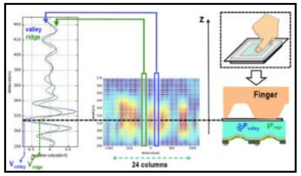
What: other MEMS physical sensors

- **Other sensors/actuators**: measurement and generation of sound or acoustic waves, or time references…

DC or AC Pressure:
MEMS barometers, microphones and ultrasound transducers

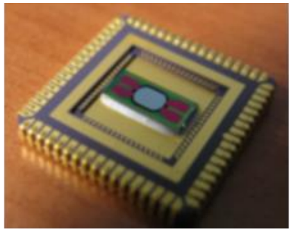


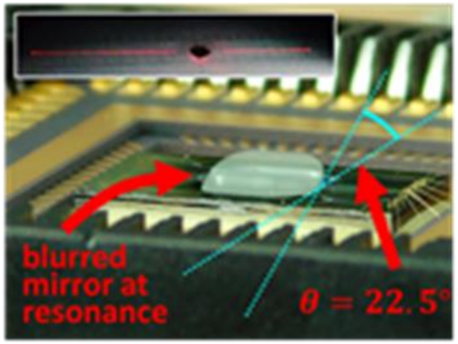




Altitude (relative height)
Smart tyres
Mobile phones
Laptops fingerprints
Intravascular echography
…

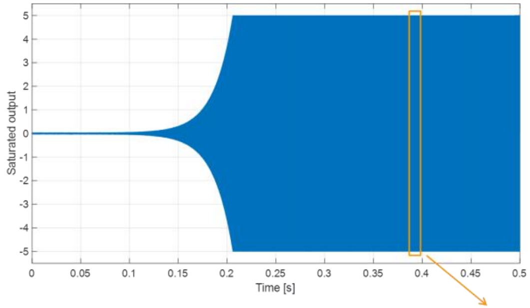
Light deflection:
MEMS micromirrors

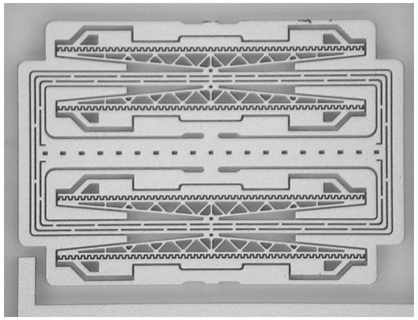


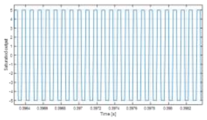


In-retina projection (AR)
Pico-pojectors
LIDAR & 3D sensing
…

Time sensors:
MEMS resonators



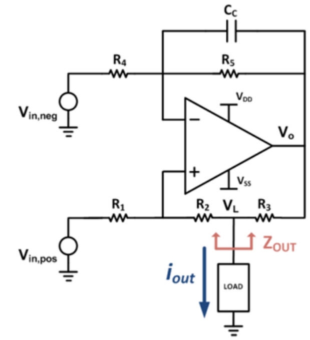




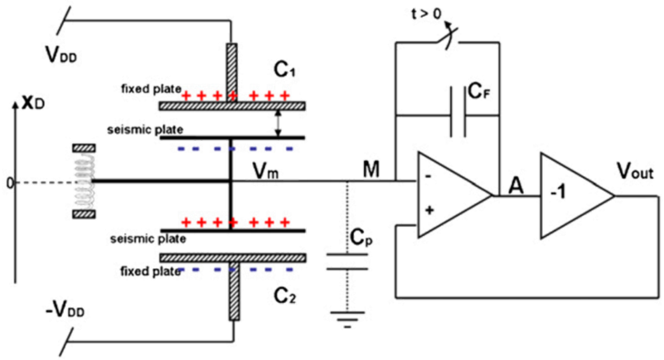
Replacement of quartz as ubiquitous clocks

What: MEMS electronics

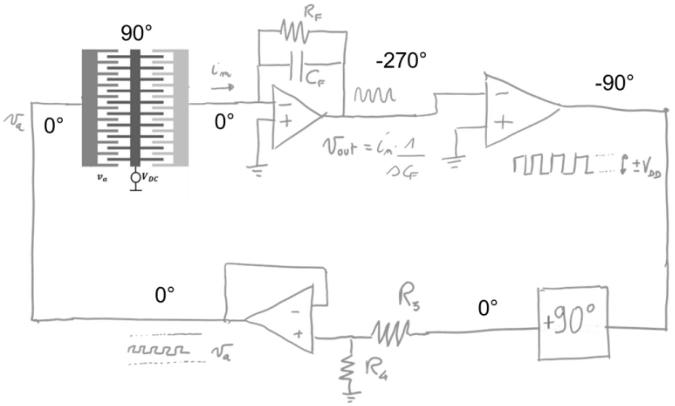
- **Drive electronics**
  - Electrostatic actuation of parallel-plate, comb-finger and membrane capacitances
  - Current driving in magnetometers



- **Sense electronics**
  - Capacitive sensing interfaces for quasi-DC sensors (e.g. accelerometers)
  - Capacitive sensing interfaces for amplitude-modulated sensors (e.g. magnetometers)
  - Noise and power considerations, trade offs



- **Harmonic oscillators**
  - Electronics for MEMS resonators
  - Drive mode of gyroscopes
  - Amplitude Gain Control circuits
  - Low-power Pierce topologies



What: the goal about MEMS

- Basic understanding of device physical working principle and operation

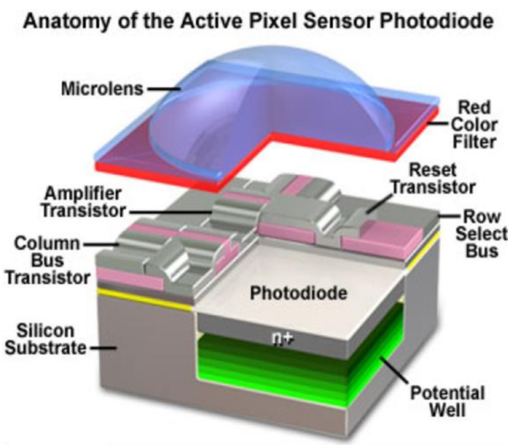
- Advanced understanding of device optimization after setting the application specifications

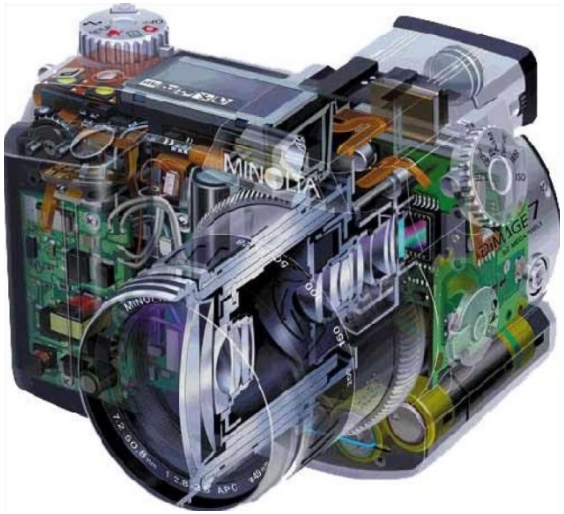
- Advanced understanding of the device/electronics co-design, trade-offs and impact on performance

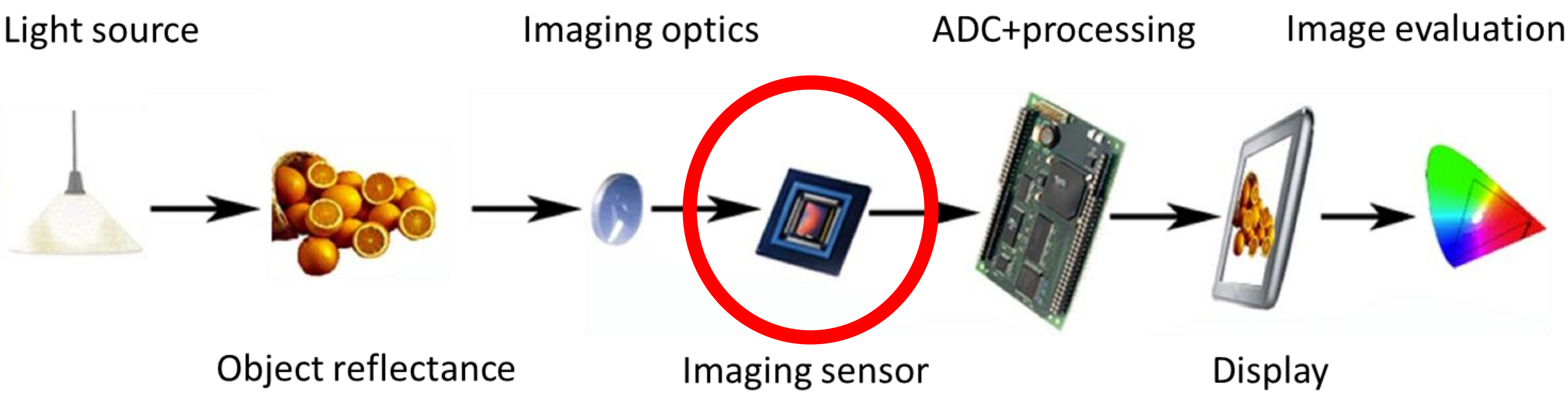
key figures: sensitivity, noise, bandwidth, linearity, full-scale range, offset…

What: CMOS imaging systems and applications

- Inside the **digital imaging pipeline**: the pixel

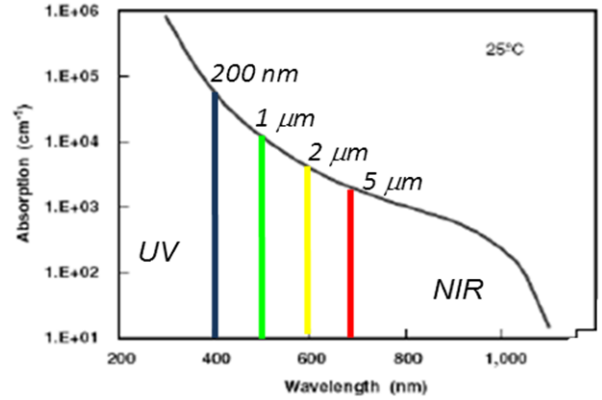


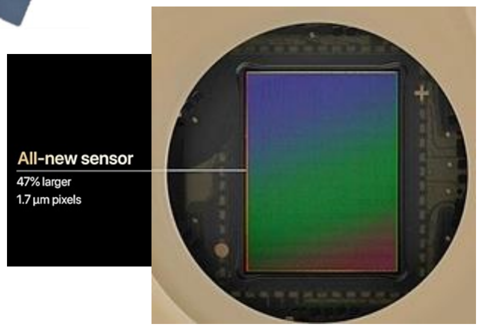


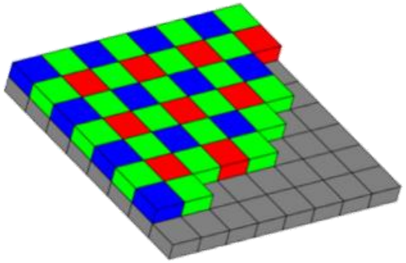


What: light focusing and absorption

- Diffraction and aberrations vs pixel size and performance
- Light absorption in Si pn junctions (photodiodes)
- Quantum efficiency and responsivity
- How to form a full color sensor
  - Color filter arrays
  - Layered junctions
  - White balance algorithms

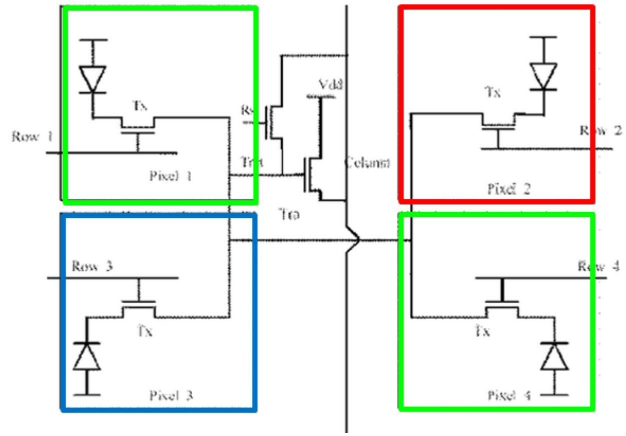


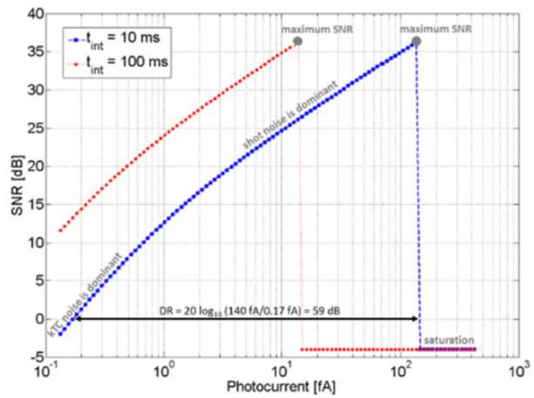


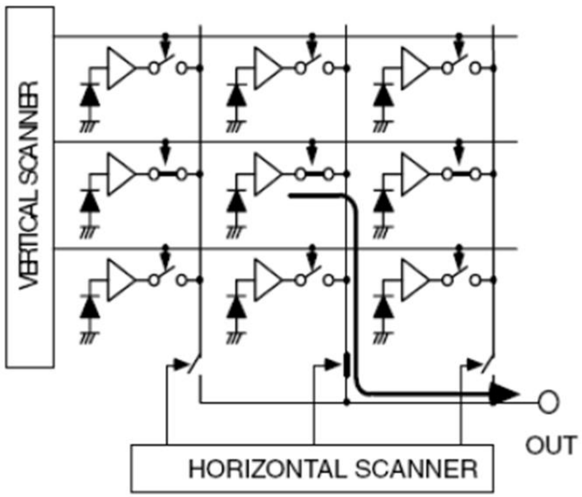


What: pixel level electronics

- Description of **N-transistor electronics** for pixels of digital cameras (N usually being 3 to 5).
  - Architecture
    - 3T, 4T…
  - Working principle
  - Key performance figures
  - Matrix arrangement
  - Future trends
    - 1.5T…







- Characteristic pixel size of a few µm, overall sensor size of few mm.

What: the goal about CMOS sensors

(the same as for MEMS sensors!)

- Basic underlining understanding of device physical working principle and operation

- Advanced understanding of device optimization after setting the application specifications

- Advanced understanding of the device/electronics co-design, trade-offs and impact on performance

key figures: SNR, DR, area, linearity, full-scale range, FPN….

Introduction to the course

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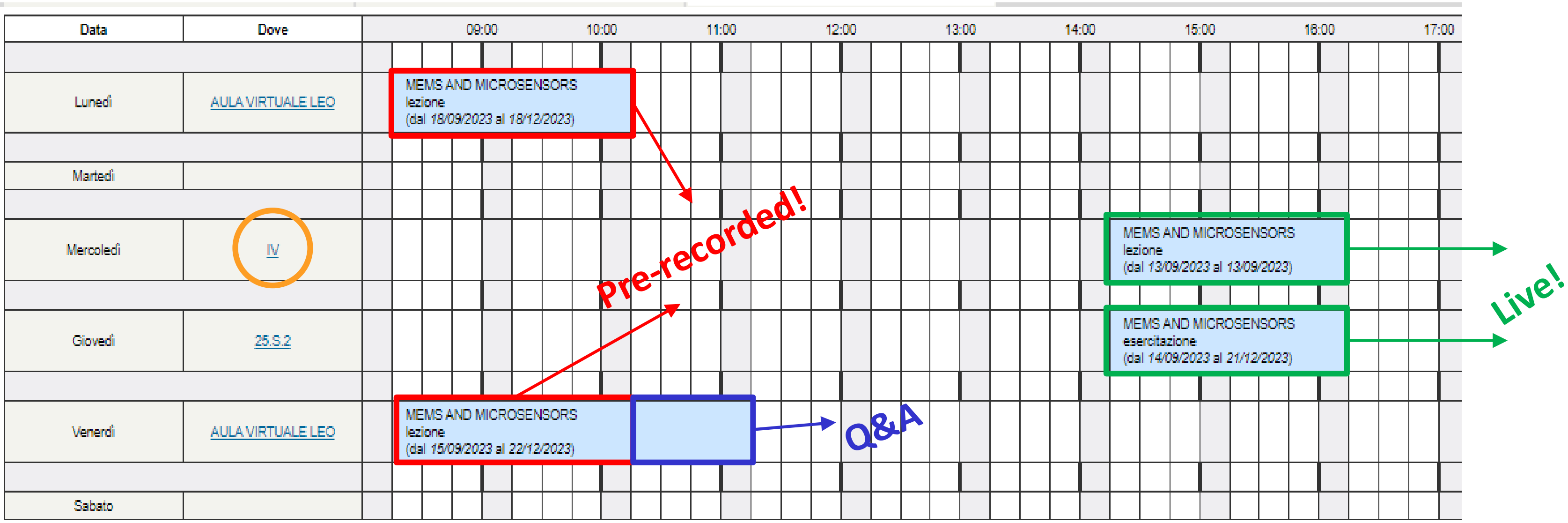
When: an exciting schedule!



- **Mon/Fri**
  - 08.15 to 10.15
  - Pre-recorded classes made available well in advance on YouTube
- **Wed/Thu**
  - 14.15 to 16.15
  - First 15-20 minutes left for self-start of the exercise solution
- **Fri**
  - 10.15 to 11.15
  - Back-up for Q&A, almost always not used
- **Notes:**
  - on the first week, the calendar foresees pre-recorded classes also on Thu (not enough matter to take numerical exercises!)
  - **on a few Mondays/Fridays, we will have live classes in Politecnico**.

Innovations in didactics: pre-recorded classes

- Pros
  - **self-organize your week**: you can watch the *MEMS and Microsensors* videos in the most suitable time (suggestion: during the official slot, or whenever before the exercises of Wednesday!);
  - have the **highest video quality**: no internet connection losses (mine or yours), no poor audio, no poor video trasmissions, no lags…;
  - **rewind and repeat**, if you have not understood some points… Suggestion: please take notes as you usually do in classes and write down questions that you want to ask!
  - have high-quality **animated slides**, instead of just having the printed slides;
  - **subtitles**: just switch them on (YouTube), they usually work fine, except for some technical words… Warning: this may help your understanding, but may distract from the slide visual content… Find your optimal setting!
  - very **good feedback from last year** attendees;
  - a **novel way of teaching**, there may be interesting surprises…

e.g.
«a MEMS sensor» may appear as
«a men's sensor»
«immense sensor»
«ms sensor»

«Coriolis force» may appear as
«cordless force»

- Cons
  - **no live interaction with the professor**… (my aim is to **solve this point on dedicated Fridays**, and by giving myself the **live numerical exercises** this year);
  - a **novel way of teaching**, there may be undesired surprises…

Notes from students of the previous courses (1)

- Student A: *"…exam procedures should have been better clarified…"*
- My comment: *"Okay, I have made available all the full 35 exams of the last years, and some exam exercises will be solved in detail in dedicated classes ..."*

- Student B: *"…I prefer live classes to pre-registered classes…"*
- My comment: *"I will teach you directly the numerical exercises this year, and a few classes and Q&A will be given live… I will do my best so that this issue is avoided!"*

- Student C: *"…sometimes exam exercises are not only a numerical application of what we have seen in classes, but they also present new topics…"*
- My comment: *"This approach tries to make you reason around (and not to merely apply) what you learned in classes, and tries to stimulate your curiosity and ideas. However, I'll take this into account"*

- Student D: *"…some background topics need to be "accepted" as are, without detailed explanations of their physical origin…"*
- My comment: *"You are partly right: however, this is a course that deals with sensors and systems. Where the physics is relevant to the understanding of the sensor operation, it will be always discussed in detail. Where it is complementary to the system, we will be forced (for the sake of time) to have only quick reviews thereof (e.g. concept of optics and lenses in a digital imaging sensor)..."*

- Student E: *"… have a "pre-exam" before Xmas. This way, you would give a chance to students to give the exam an advance, easying the winter session of Jan/Feb, very crowded with Zappa and Lacaita.…"*
- My comment: *"This pre-exam was introduced 2 years ago, and this year I will do it again"*

Notes from students of the previous courses (2)

- Student F: *"…it would be useful to have the material pre-loaded on the website few days in advance…"*
- My comment: *"This year you will have all the slides pre-uploaded on the website much before their official date, as well as the pre-recorded lectures. Solutions of numerical exercises, instead, will be uploaded on the website a few days after they are discussed in the classrooms."*

- Student G: *"…during CAD exercise, it would be better to let us solve the problem without too much help from the assistants…"*
- My comment: *"very good suggestion! We will leave more time for you to independently solve the problems, so to better learn the CAD use. The number of CAD classes is increased from 4 to 7, and you will have more room to practice yourself."*

- Student H: *"…the 1st exam of the 1st session was too early, right after the end of the classes…"*
- My comment: *"Okay, I have no problem in redistributing the two exams of the first session on a wider timescale, if this helps you with the exam preparation. Note that this year you will also have the pre-exam…"*

- Student J: *"…some pre-recorded classes last too long…"*
- My comment: *"I know this… but there are others which last less. Anyway, this year the program will be reduced with 2-3 less theoretical classes, substituted by seminars given by people from the flourishing sensors industry field in the Milano area…"*

When: tentative full program

	day	weekday	time	room	type	topic	notes and details
2	13/09/2023	Wed	14:30-16:00	IV	LL	**L01 Introduction to the course**	Course organization, classes, exams, material, program. Status of the MEMS and CMOS market. Key applications and course overview.
4	14/09/2023	Thu	14:30-16:00	virtual	RL	**L02 Technologies for MEMS sensors**	Overview of a sample MEMS process. Main steps: epitaxial growth, DRIE, bonding, packaging.
6	15/09/2023	Fri	08:30:10:00	virtual	RL	**L03 The spring-mass-damper system**	Inertial and non-inertial references. Spring-mass-damper system in the time and frequency domains. Quality factor (underdamped and overdamped systems). Role of electrostatic forces in the system.
8	18/09/2023	Mon	08:30:10:00	virtual	RL	**L04 MEMS accelerometers: part 1**	General architecture: capacitance variation vs displacement. Charge amplifier differential readout. Pull-in effects. Electrostatic softening and overall sensitivity. Linearity of a parallel-plate configuration.
10	20/09/2023	Wed	14:30-16:00	virtual	RL	**L05 MEMS accelerometers: part 2**	Accelerometer bandwidth and choice of the quality factor. Thermomechanical noise in MEMS. Trade-offs vs applications. Comb finger readout.
12	21/09/2023	Thu	14:30-16:00	25.S.2	LE	**E01 MEMS accelerometer design**	Design of an in-plane MEMS accelerometer to satisfy a specific application with a specific process.
14	22/09/2023	Fri	08:30:10:00	virtual	RL	**L06 MEMS accelerometers: part 3**	Sample configurations of springs: in-plane translation, out-of-plane translation and rotation. Series and parallel of springs. Sample acceleroemters architectures. Effects of process nonuniformities on springs. Folded springs.
16	25/09/2023	Mon	08:30:10:00	virtual	RL	**L07 MEMS accelerometers: part 4**	The problems of scaling and pull-in. Charge control vs voltage control: effects of parasitics. Switched capacitor circuits. Force feedback.
18	27/09/2023	Wed				**B.S. Graduation day**	No classes
20	28/09/2023	Thu	14:30-16:00	25.S.2	LE	**E02 MEMS accelerometers electronic readout**	Circuits for MEMS accelerometers: description and exercise, noise limitations (MEMS and electronics), dynamics considerations.
22	29/09/2023	Fri	08:30:10:00	tbd	QA	**UN-related goals**	Autonomous driving and its impact on the society for cities of the future. Associated sensor needs. Sensors in biomedical applications. Sensors for sustainable infrastructures
24	02/10/2023	Mon	08:30:10:00	virtual	RL	**L08 MEMS resonators: part 1**	Comb-finger actuation and sensing. Transduction coefficient and calculation of the admittance. Equivalent electrical model in the frequency domain.
26	04/10/2023	Wed	14:30-16:00	IV	LE	**E04 Torsional MEMS accelerometer design**	Torionsal springs. Calculation of the sriffness and of the moment of inertia for simple configurations. Numerical exercise.
28	05/10/2023	Thu				**M.S. Graduation day**	No classes
	06/10/2023	Fri	08:30:10:00	virtual	RL	**L09 MEMS resonators: part 2**	Oscillator circuits: Barkhausen criteria. Sample TIA plus nonlinearity example. Issues of linearity. Example of resonant accelerometer.
30	09/10/2023	Mon	08:30:10:00	virtual	RL	**L10 MEMS resonators: part 3**	Effects of the feedthrough capacitance on the electrical model of the resonator, and on the Gloop of the oscillator. Common resonator configurations.
32	11/10/2023	Wed	14:30-16:00	IV	LC	**E03 CAD simulation of MEMS capacitances**	Review of capacitive sensing configurations in MEMS. Ideal laws and deviations due to fringe effects. Case study for vertical parallel plates.
34	12/10/2023	Thu	14:30-16:00	25.S.2	LE	**E05 Resonator design**	Dimensioning of a Tang resonator to be used in a 32 kHz clock, with process spread and tunability.
36	13/10/2023	Fri	08:30:10:00	virtual	RL	**L11 MEMS gyroscopes: part 1**	Generalities and the Coriolis force. Sample architecture. Resonant operation. Drive displacement. Sensitivity.
38	16/10/2023	Mon	08:30:10:00	virtual	RL	**L12 MEMS gyroscopes: part 2**	Issues from accelerations and advanced architectures. Single and double decoupling. In-plane and out-of-plane architectures. Tuning fork. Capacitive PP sense detection. Overall sensitivity.
40	18/10/2023	Wed	14:30-16:00	IV	LE	**E06 Oscillator circuit**	Dimensioning of an oscillator based on a CA configuration. Comparative discussion with respect to the TIA case.
42	19/10/2023	Thu	14:30-16:00	25.S.2	LE	**E07 Gyroscopes electromechanical design**	Push pull actuation and sizing of relevant electromechanical parameters.
44	20/10/2023	Fri	08:30:10:00	virtual	RL	**L13 MEMS gyroscopes: part 3**	Gyroscope bandwidth. Sensitivity and gain-bandwidth trade-off. Electronics and thermomechanical noise.
46	23/10/2023	Mon	08:30:10:00	virtual	RL	**L14 MEMS gyroscopes: part 4**	Issues in resonance operation (temperature dependence). Off-resonance operation. Gyroscope bandwidth. Sensitivity and gain-bandwidth trade-off.
48	25/10/2023	Wed	14:30-16:00	IV	LC	**E08 CAD simulation of MEMS accelerometers**	Introduction to CAD FEM simulations for MEMS. Examples on an accelerometer.
50	26/10/2023	Thu	14:30-16:00	25.S.2	LE	**E09 Drive circuits for gyroscopes**	Oscillators for gyroscopes. Relevance of AGC circuits and solutions. AGC stability.
52	27/10/2023	Fri	08:30:10:00	self-activity	LC	**E10 CAD simulation of torsional accelerometers**	Autonomous design of an out-of-plane MEMS accelerometer with capacitive readout for consumer applications.
54	30/10/2023	Mon	08:30:10:00	virtual	RL	**L15 MEMS gyroscopes: part 5**	Themormechanical noise in mode-split operation. Electronic noise in mode-split operation. Examples of real measurements.
	01/11/2023	Wed				**All saints holidays**	No classes
56	02/11/2023	Thu	14:30-16:00	25.S.2	LC	**E11 CAD simulation of MEMS yaw gyroscopes**	Design of a MEMS gyroscope. Parametric approach and finalisation of the geometry.
58	03/11/2023	Fri	08:30:10:00	self-activity	LC	**E12 CAD simulation of pitch MEMS gyroscopes**	Autonomous design of a MEMS gyroscope.
60	06/11/2023	Mon				**Suspension of classes**	No classes
	08/11/2023	Wed	14:30-16:00	IV	LL	**L16 MEMS gyroscopes: part 6**	Quadrature error. Origin. Modelling. Coupling with phase noise. Quadrature error compensation. Tatar scheme.
62	09/11/2023	Thu	14:30-16:00	25.S.2	LE	**E13 Sense circuits for gyroscopes**	Sensing and demodulation electronics for capacitive gyroscopes. Noise considerations.
64	10/11/2023	Fri	08:30:10:00	virtual	RL	**L17 MEMS magnetometers: part 1**	Lorentz force and resonant working principle. Simplified architecture. Sensitivity. Comparison with Coriolis and inertial forces. Noise, offset.
66	13/11/2023	Mon	08:30:10:00	virtual	RL	**L18 MEMS magnetometers: part 2**	Off-resonance operation and solutions of the trade offs. Design criteria. Integrated electronics. Comparison with other technologies (AMR, Hall).
68	15/11/2023	Wed	14:30-16:00	IV	RL	**Seminar from industry n. 1**	tbd
70	16/11/2023	Thu	14:30-16:00	25.S.2	LE	**E15 MEMS microphone**	Exercise on a sensor not treated in the course, to stimulate the students approach towards other sensors developed in the same technology.
72	17/11/2023	Fri	08:30:10:00	virtual	RL	**L20 MEMS characterization and the Allan Variance**	The next killer application: the IMUs. Stability issues. Offset drift and the Allan variance. Definition, relation with white noise, and use.
74	20/11/2023	Mon	08:30:10:00	virtual	RL	**L21 Light sensors basics: part 1**	Human vision. Description of the eye, photoreceptors, concept of a color space, stimuli to the brain. Basics of light sources.
76	22/11/2023	Wed	14:30-16:00	IV	RL	**Seminar from industry n. 2**	tbd
78	23/11/2023	Thu	14:30-16:00	virtual	RL	**L22 Light sensors basics: part 2**	CMOS image sensors. System architecture. Basics of optics and diffraction. Number of photons on a pixel.
80	24/11/2023	Fri	08:30:10:00	virtual	RL	**L23 CMOS 3T APS: part 1**	Interaction of light in semiconductors. Absorption law. Simple photodiode and typical dimensions. Signal generation and noise overview.
82	27/11/2023	Mon	08:30:10:00	virtual	RL	**L24 CMOS APS: part 2**	3-transistor APS topology. Transistor-level architecture. Operation. Phases. Linearity. Signal to Noise ratio.
84	29/11/2023	Wed	14:30-16:00	IV	LC	**E16 CAD light absorption in Silicon**	Preliminaty CAD to imaging sensors
86	30/11/2023	Thu	14:30-16:00	25.S.2	LE	**E17 photons on a pixel**	Calculation of the number of photons generated per second on a pixel of a mobile phone camera from a generic scene.
88	01/12/2023	Fri	08:30:10:00	tbd	LS	**Seminar from industry n. 3**	tbd
90	04/12/2023	Mon	08:30:10:00	virtual	RL	**L25 CMOS APS: part 3**	Dynamic range of a 3T image sensor. Other limitations: fixed pattern noise. Photon transfer curve.
92	06/12/2023	Wed	14:30-16:00	IV	LE	**E18 SNR in a 3T topology**	Calculating the Signal to Noise Ratio for a 3T CMOS pixel topology. Numerical examples.
94	11/12/2023	Mon	08:30:10:00	virtual	RL	**L26 CMOS APS: part 4**	Limits of a 3T topology and introduction of 4T topologies. Correlated Double Sampling. Backside illumination and advantages.
96	13/12/2023	Wed	14:30-16:00	IV	LE	**E20 DR and maximum SNR in 3T APS**	Maximum SNR and dynamic range of a 3T CMOS pixel. Choice of the ADC number of bit.
98	14/12/2023	Thu	14:30-16:00	25.S.2	LE	**E21 photon transfer curve**	Example of a circuit for correlated double sampling in CMOS APS 4T topologies with calculation of DR. PTC and its analysis.
100	15/12/2023	Fri	08:30:10:00	virtual	RL	**L27 CMOS APS: part 5**	CFA for CMOS image sensors. Demosaicking. Layered junction sensors (working principle). General pros and cons of the two approaches. Color conversion and color spaces. White balance.
	18/12/2023	Mon	08:30:10:00			**Backup slot**	No classes
	20/12/2023	Wed	14:30-16:00	self-activity	LC	**E19 CAD simulations of advanced imaging pixels**	Autonomous design of a Pinned photodiode
102	21/12/2023	Thu	14:30-16:00			**Backup slot**	No classes
102	22/12/2023	Fri	08:30:10:00	tbd	XM	**Anticipated exam session**	

- The course is covered within 102 hours, including a few hours of dedicated Q&A.
  - No classes during the suspension week (one seminar foreseen). No class on October 6th (graduation day).
  - Course ends on Dec 17th.
- An anticipated exam before Christmas is foreseen on Dec 21st to help you better manage the winter exam session.

- **This is a provisional program, subject to small changes! The program may be subject to updates, always available online!**

Note: shortening the program

- In comments from students we are often said that the program is dense (this is valid for almost all courses at Electronics Engineering…, by the way)

- To alleviate the course workload, I decided to remove magnetometers from the program. Thus, **classes n. 17, 18 and 19 will be not part of the program**. The registered lectures will be anyway available for those who <u>**facultatively**</u> want to deepen that topic.

- Consequently also one numerical exercise related to magnetometers was removed.

- Part of those hours will be used for **seminars from the industry** and to introduce to you the research and **thesis opportunity of our lab**.

Introduction to the course

- Who
- What
- When
- **Where**
- Why

Where: website for slides download and videos links

- Live, **highly interactive**, **numerical exercises and labs** (anyway recorded and online)
  - Wed
    - Room IV
  - Thu
    - Room 25.S.2


POLITECNICO MILANO 1863
DIPARTIMENTO DI ELETTRONICA INFORMAZIONE E BIOINGEGNERIA
MEMS Lab
Laboratory of MEMS and Microsensors

Home | Research | Education | Equipment | People | Publications | Contacts

MEMS and Microsensors 2022-2023

Professor: Giacomo Langfelder
Laboratory Assistants: Sara Cozzi, Christian Padovani, Andrea Buffoli

The aim of the course is to introduce the basic concepts of various types of electronic devices which allow to acquire physical, chemical and biological information from the outside world and also to act on it at microscopic level. The attention is focused on the operating principles of (CMOS) optical image sensors and of Micro-Electro-Mechanical-Systems (MEMS). Their integration in more complex systems and with their electronics is also considered. The performances of these devices are discussed with particular reference to their various societal fields of application. Class-works about specific case-studies as well as experimental CAD laboratory activities are foreseen. Dedicated classes to relate the course matter to the ONU Agenda 2030 will be also presented.

News and Communications

Welcome folks, in this page you will find the links to the videos, the slides of the lectures, and the detailed and discussed solutions of numerical exercise and CAD classes! More information on the organization of the course can be found here!

All the slides and videos are made available well in advance with respect to the corresponding class date. The numerical exercises solutions are uploaded right after the corresponding classes.

The most updated course schedule is always available here!

Helpful slides, reviewing basics of electronics for non-electronic students, and focusing on the purpose of the course, have been added! Check further below on this page!

Slides (and link to Videos) of the course (and Q&A sessions)

C01 Course Introduction (link to video)

C02 MEMS Technology (link to video)
C03 MEMS Spring Mass Damper (link to video)
C04 MEMS Accelerometer Part 1 (link to video)
C05 MEMS Accelerometer Part 2 (link to video)
C06 MEMS Accelerometer Part 3 (link to video)

NEWS from the lab...

05-09-2022 two contributions from the lab accepted at the 2022 ICECS conference to be held next October in Glasgow! Congrats to Matteo Gianollo and all co-authors!

10-06-2022 good luck to Paolo Frigerio, who has just become an Assistant Professor with the DEIB department!

01-05-2022 we welcome Riccardo Nastri, who joined the laboratory as a PhD student!

08-05-2022 three contributions from the lab were presented at the 9th IEEE International Symposium on inertial sensors and systems: congratulations to all co-authors! Special cheers to A. Buffoli for the first runner-up award!

20-06-2021 best poster award granted to our presentation at the 2021 Transducers conference! Congratulations to Paolo Frigerio, Matteo Gianollo and all other co-authors!

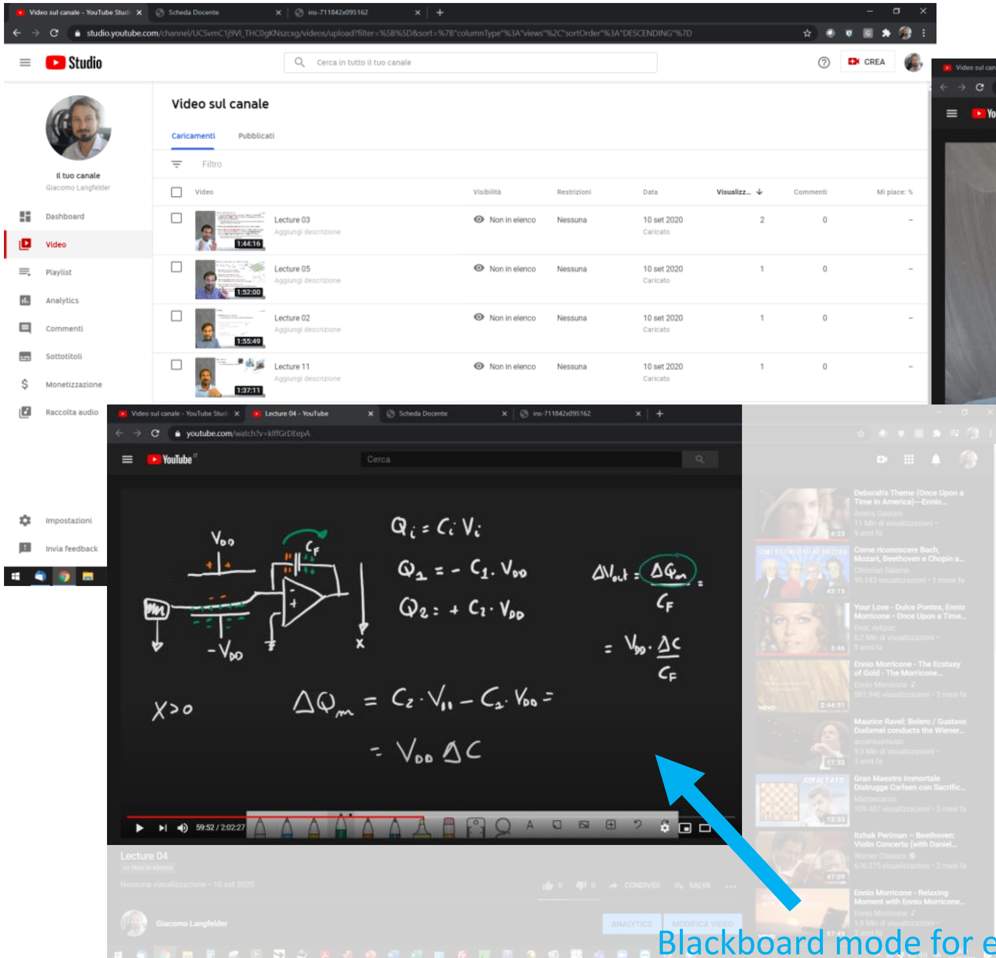
01-05-2021 we welcome Christian Padovani and Andrea Buffoli, joining the lab with PhD focused on high performance inertial sensors!

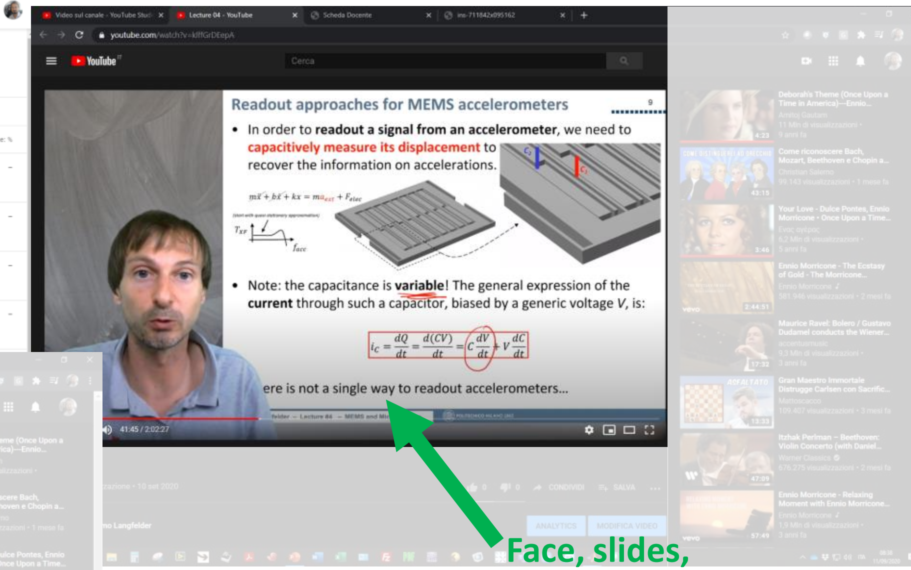
24-09-2020 two contributions from the MEMS lab have been accepted for lecture presentation at IEEE Sensors 2020, to be held this October. Congrats to both Marco Gadola (M&NEMS gyroscopes) and Paolo Frigerio (MEMS-based RTCs) for their research!

08-09-2020 the first thesis student who started the M.S. Thesis during the lockdown is today on his first lab day! Welcome back to the MEMS laboratory, stay safe and take

- On the website:
  - ***https://www.sensorlab.deib.polimi.it/***
  - Slides PWD: ***MMXX*** (case sensitive)
  - CHECK IF IT WORKS PROPERLY (I MANAGE THE WEBSITE MYSELF…)

Where: on YouTube!

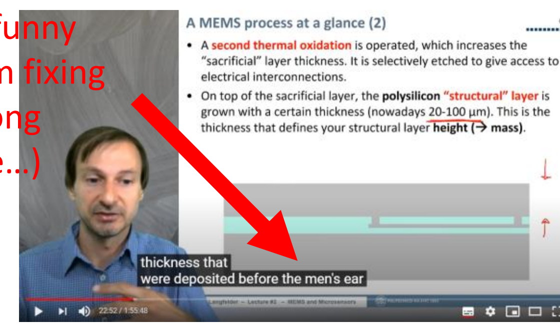




Face, slides,
and pen-over-slides for most of the time

Blackboard mode for equations,
drawings and demonstrations

Example of funny subtitles… I am fixing them (a long procedure…)



- NOTE: *not-in-list mode*, accessible **only via the provided links**. **Please do not share videos with people not attending the course**.

Where: laboratories

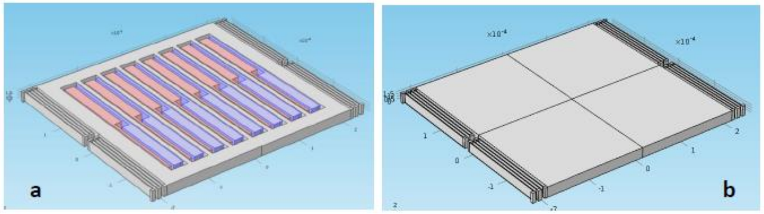
- On **seven** days, you will have CAD classes/exercises. The **number of laboratories** has been **doubled** with respect to past years!

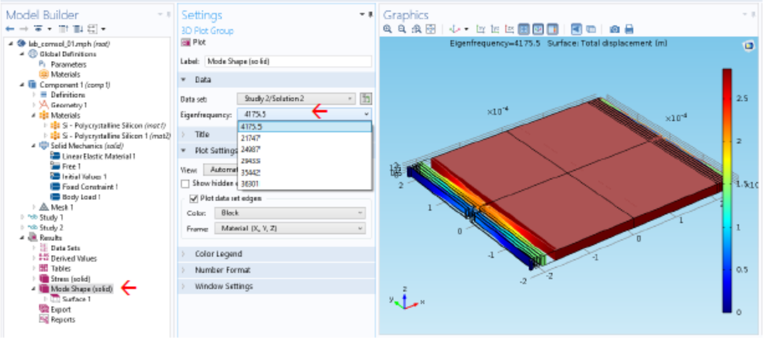
- The aim is to let you **learn and use tools for sensor design and simulation**.

- Classes last 2 hours (please, be in the room by 14.10: lab classes start at 14.15).

- **Bring your own PC** (at its maximum charge…)!

Please exploit the opportunity to learn more: train yourself whenever you want as you have a 6-month full free license!





Software download steps:

- Get the POLIMI license (I need myself to communicate your emails to the Polimi Software Service, and I will send you a passcode for the registration)

- Install the Software (Comsol, version 5.xx)

- https://www.software.polimi.it/software-download/studenti/comsol/index.html

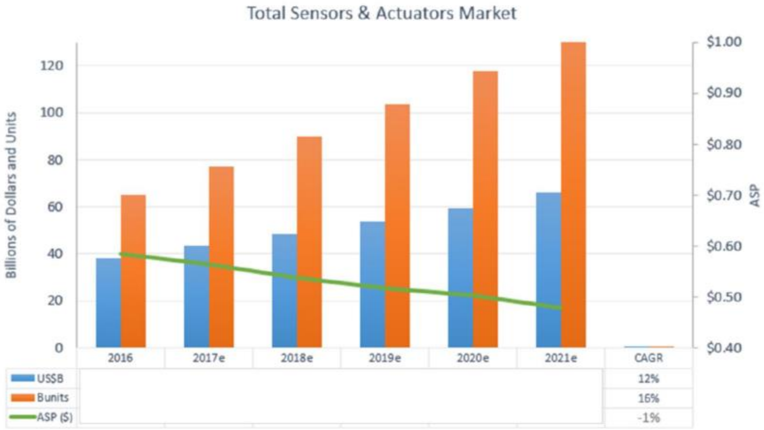
- I will get back to you with more details in the following days

Introduction to the course

- Who
- What
- When
- Where
- Why

Why

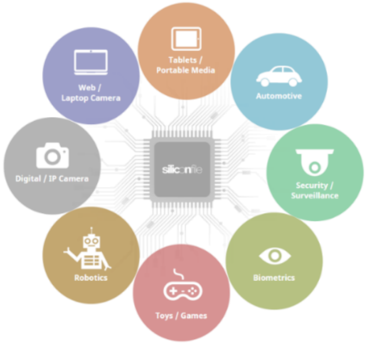
- Importance of **MEMS and digital imaging** sensors for the community
  - **sensors are ubiquitous** and the quality of our everyday-life somewhat depends also on them;
  - sensors represent about 10% of the revenues of the IC industry. The percentage is foreseen to grow to 15% in 5 years

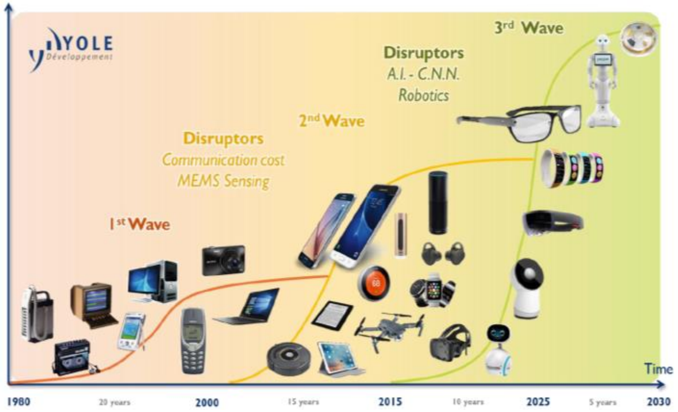


- Importance of MEMS and digital imaging for you
  - to learn
  - to pass the exam
  - to find a job (a lot of opportunities in the greater Milano area)

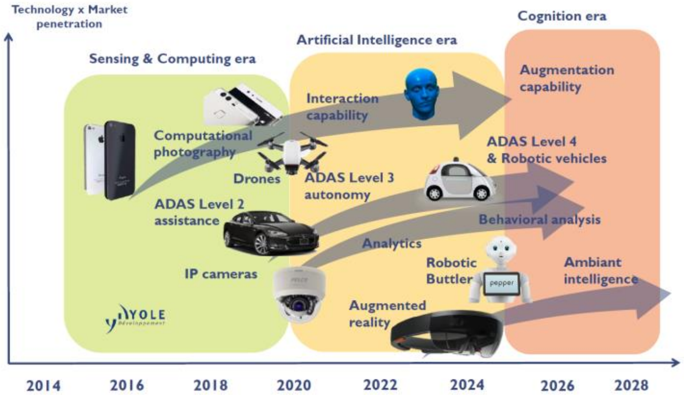
Why: enormous number of applications

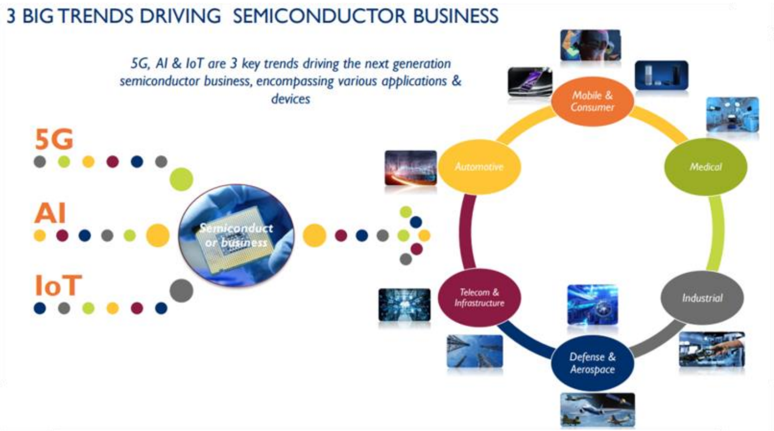
MEMS





CMOS



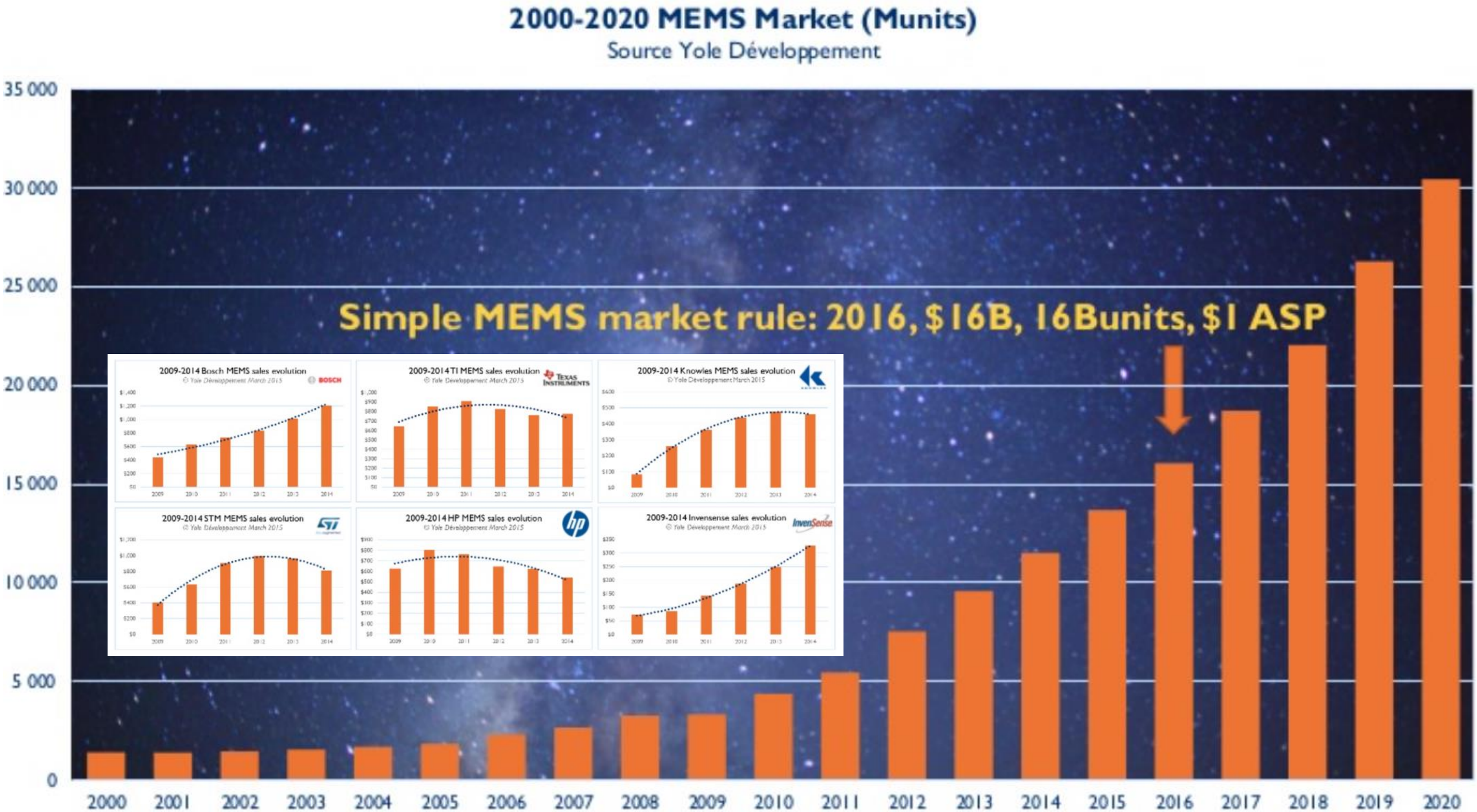


- Increasing number of applications for both the sensor technologies…

Why: ONU related goals!

Why: business facts in MEMS sensors industry

- Increasing business (and job opportunities) around MEMS market.



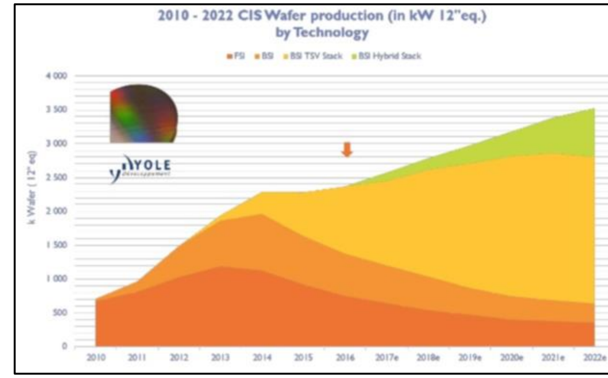
Milano area and the MEMS industry

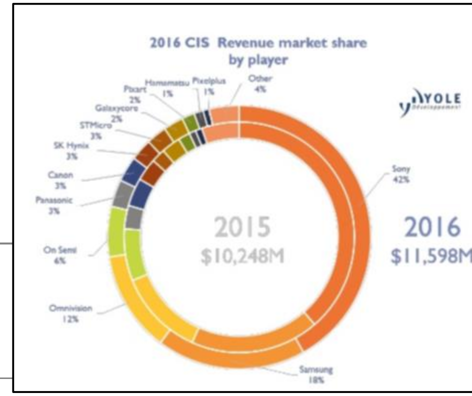
- ST Microelectronics
  - 2 sites (fab and design center)
- TDK Invensense
  - design center (MEMS + IC)
- BOSCH Sensortec
  - design center (MEMS + IC)
- Analog devices
  - design center (IC only)

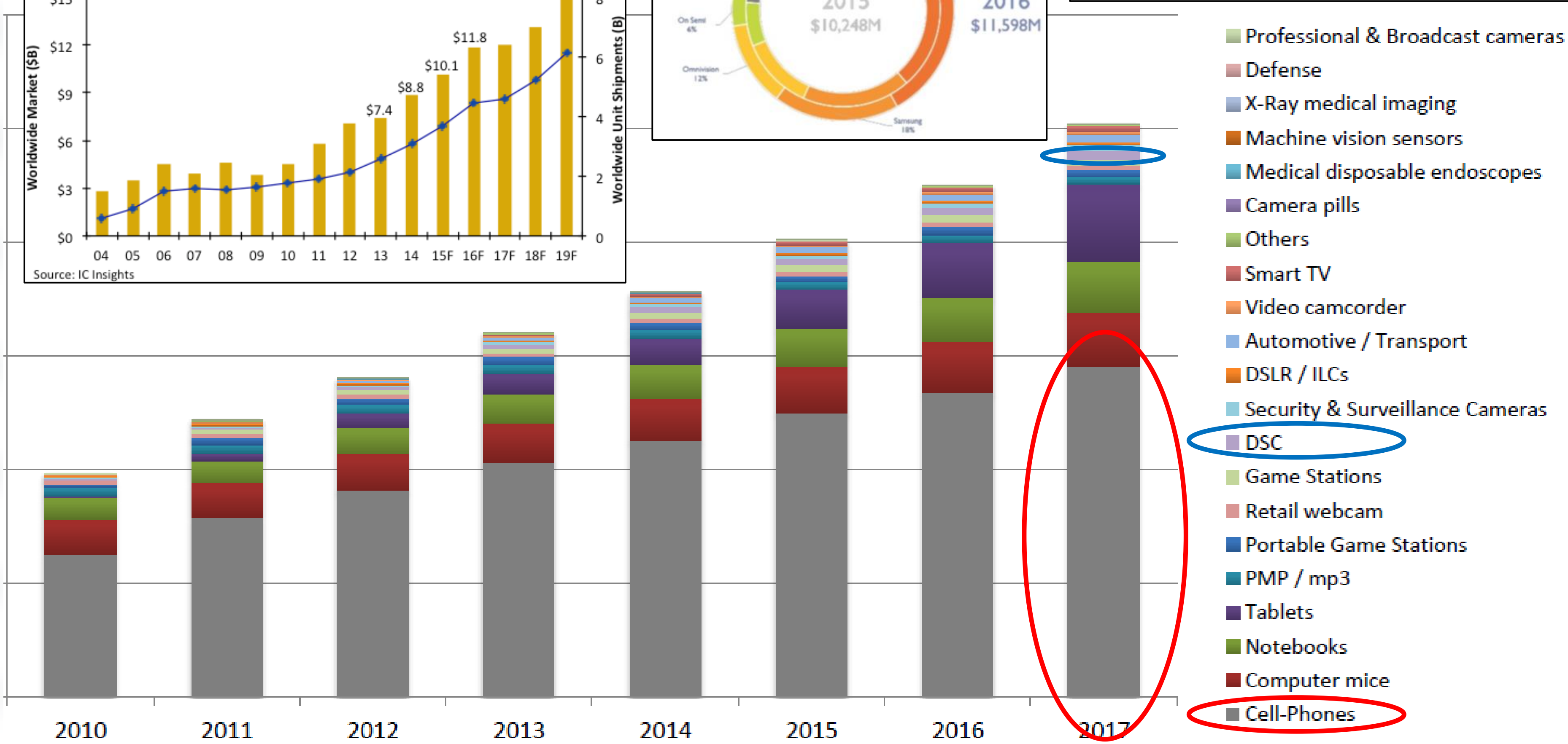
- Other university sites
  - Milano Bicocca, Pavia, Padova, Brescia, Torino, Bologna…

Why: business facts in CMOS sensors industry

- Increasing business (and job opportunities) around the CMOS market.





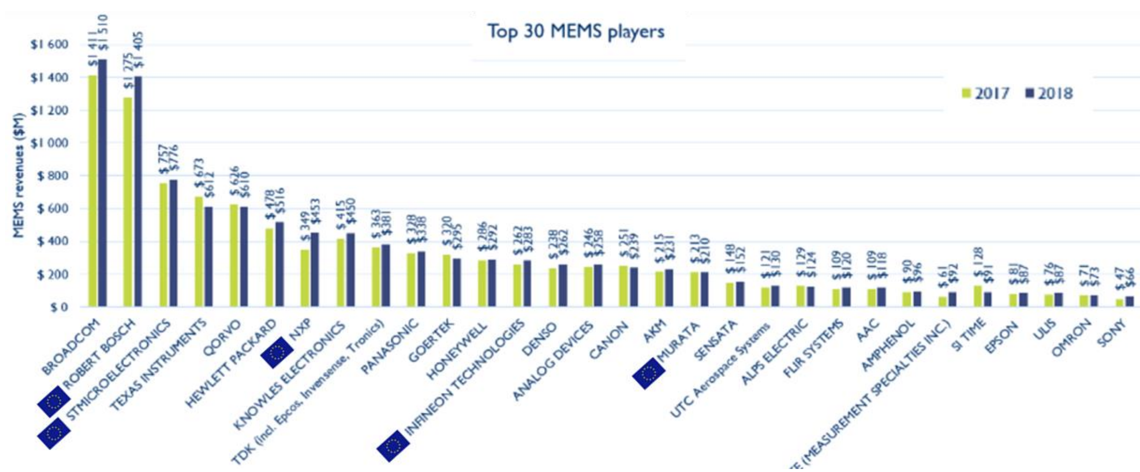


Why: sensor development around the world

- Geographic mapping

Europe is still quite competitive in both the fields!!
Italian leadership in MEMS!!

- European leadership in MEMS



Why

- To learn:
  - Detailed (explained) **<u>slides, videos, and discussed numerical exercises</u>**.
    - Specific references and further reading for some topics.
    - Detailed solutions of former exams (especially for theory).

  - Some reference books or scientific papers (*<u>it is not necessary to buy any of these books however – if not for personal interest</u>: they only cover small portions of the course*):
    - Volker Kempe, **Inertial MEMS**, Cambridge University Press, 2011
    - Cenk Acar, Andrej Shkel, **MEMS Vibratory Gyroscopes**, Springer, 2009
    - G. Langfelder, A. Tocchio, **Smart Sensors and MEMS, chapter 13 - MEMS integrating motion and displacement sensors**, Pages 366-401, 2014, Woodhead publishing.
    - Juniki Nakamura, **Image sensors and signal processing for digital cameras**, CRS Press, Taylor&Francis, 2006
    - R.C.Gonzalez, R.E.Wood, **Digital Image Processing**, Prentice Hall, 2007
    - A. El Gamal and H. Eltoukhy, **CMOS image sensors**, IEEE Circuits & Devices Magazine, 2005.

Why

- The exam
  - Written exam with 2 exercises and 1 theory question
  - Evenly distributed scores for them: 10 points each (max score of the written exam is 30). No “honors” without oral exam.
  - Possible oral exam for “honors” (30 e Lode)
    - students with ≥ 26 can take a (facultative) oral exam;
    - the oral exam can increase or decrease the mark.

- Some past exam numerical exercises will be given and solved with the teaching assistants after roughly 50% of the classes.
  - last 35 exams are available on the website.

- **Anticipated exam session before Xmas**!

Check the rules for 110 L graduation! Some 30 L in the career makes this easier!

MEMS & Microsensors 2023-2024

ENJOY THE CLASSES!

PLEASE, ASK QUESTIONS…
…EVEN IF IN A NEW WAY!