上海科技大学
ShanghaiTech University

CS283: **Robotics Spring 2025**

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ShanghaiTech University

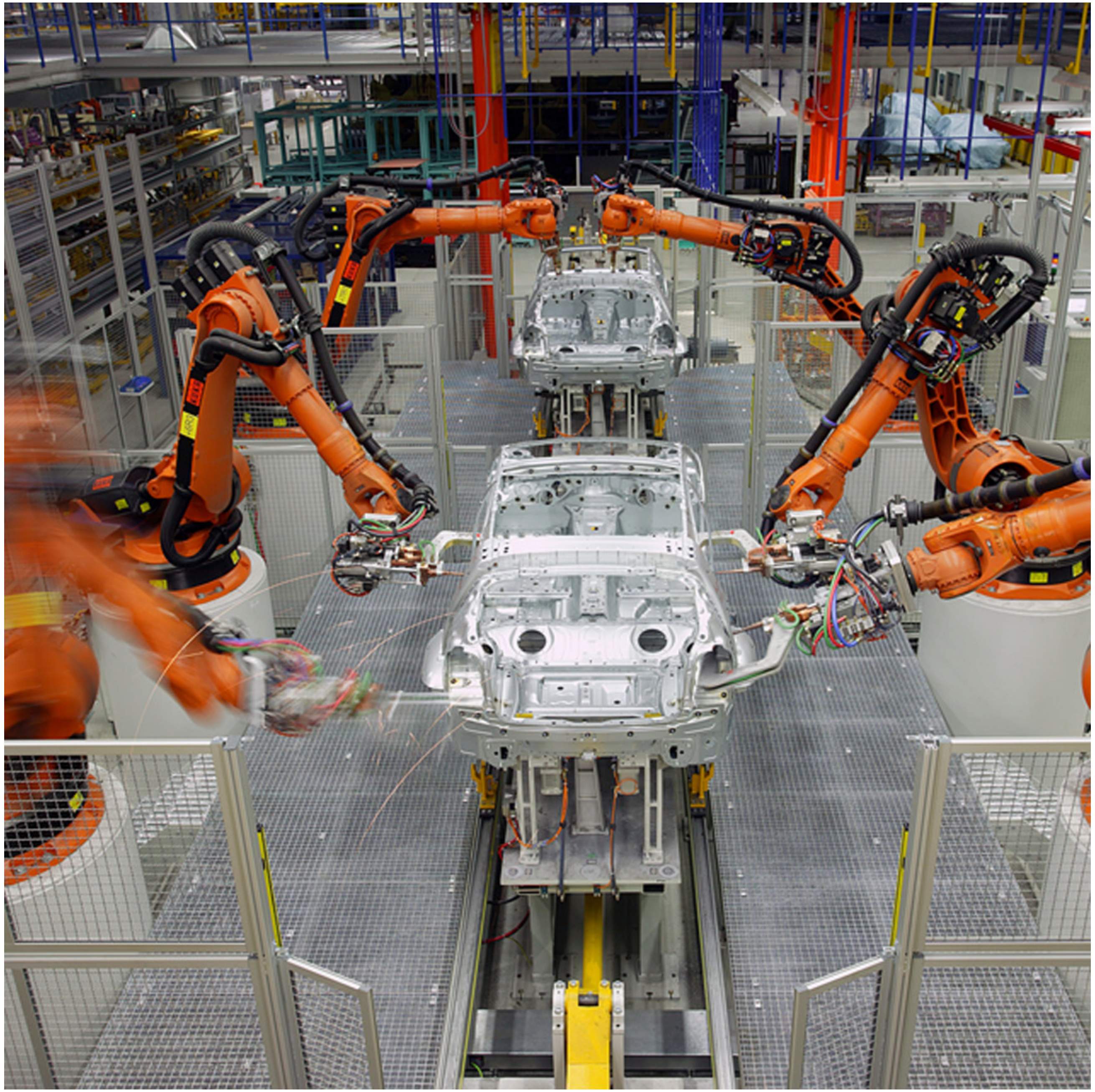
STAR CENTER

Outline

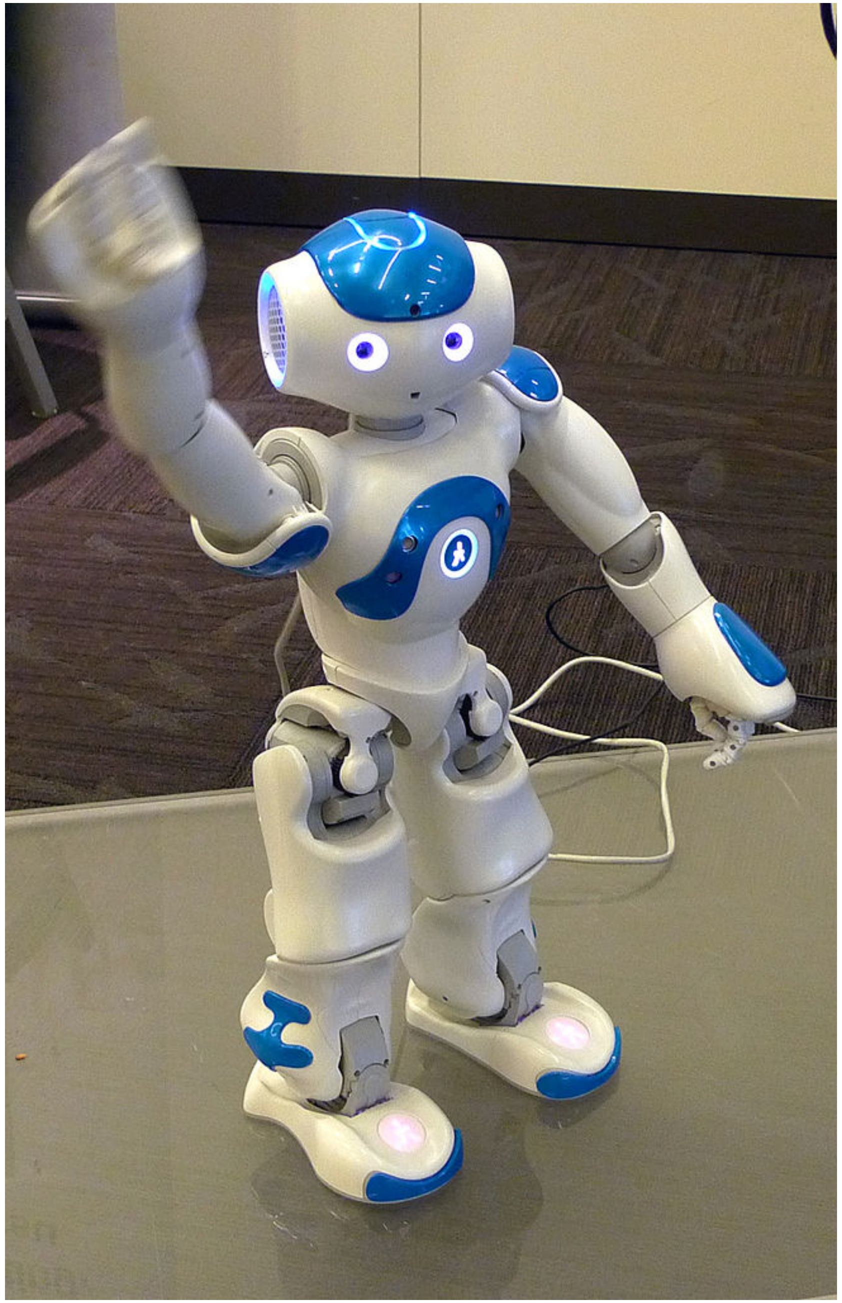
- What is a Robot?
- Why Mobile Robotics?
- Why Autonomous Mobile Robotics?
- Course Overview
- Brief History
- Software

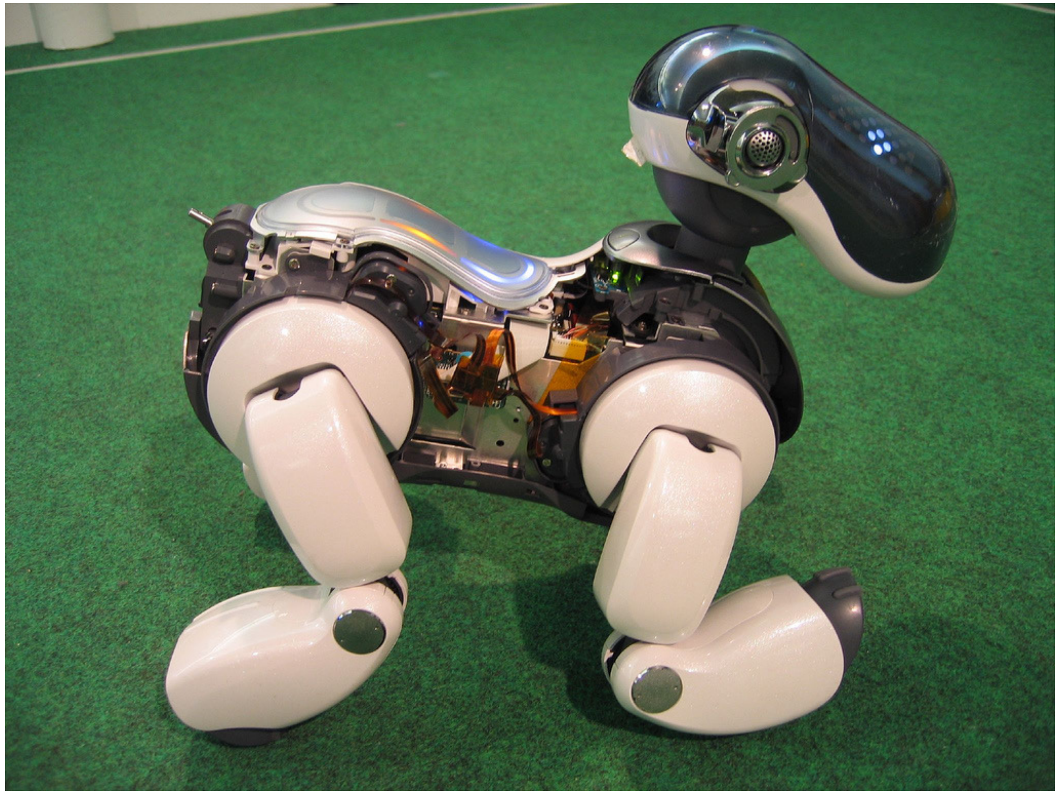
What is a Robot?

Pictures on the following slides all from http://commons.wikimedia.org




ASIMO
HONDA

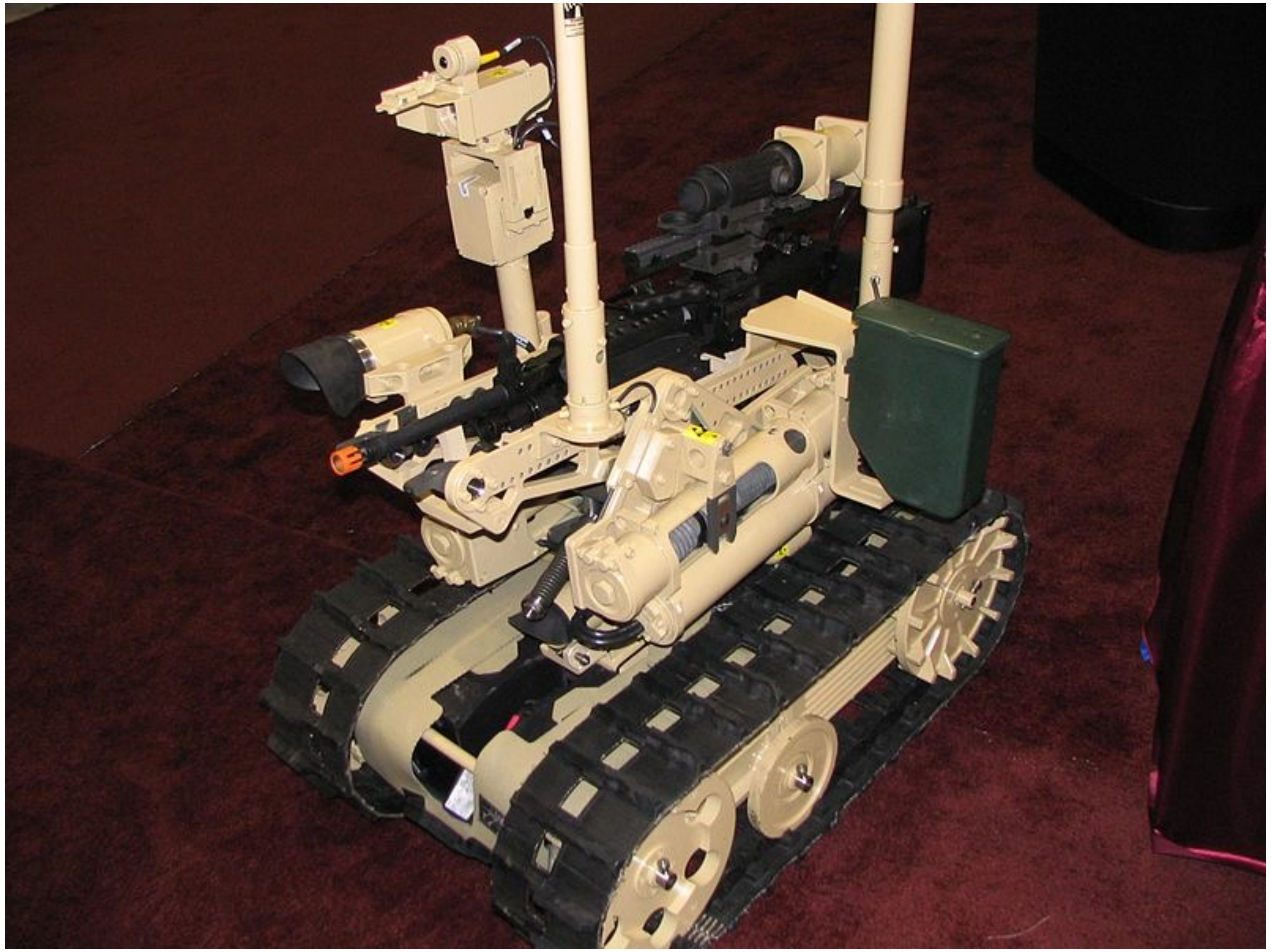




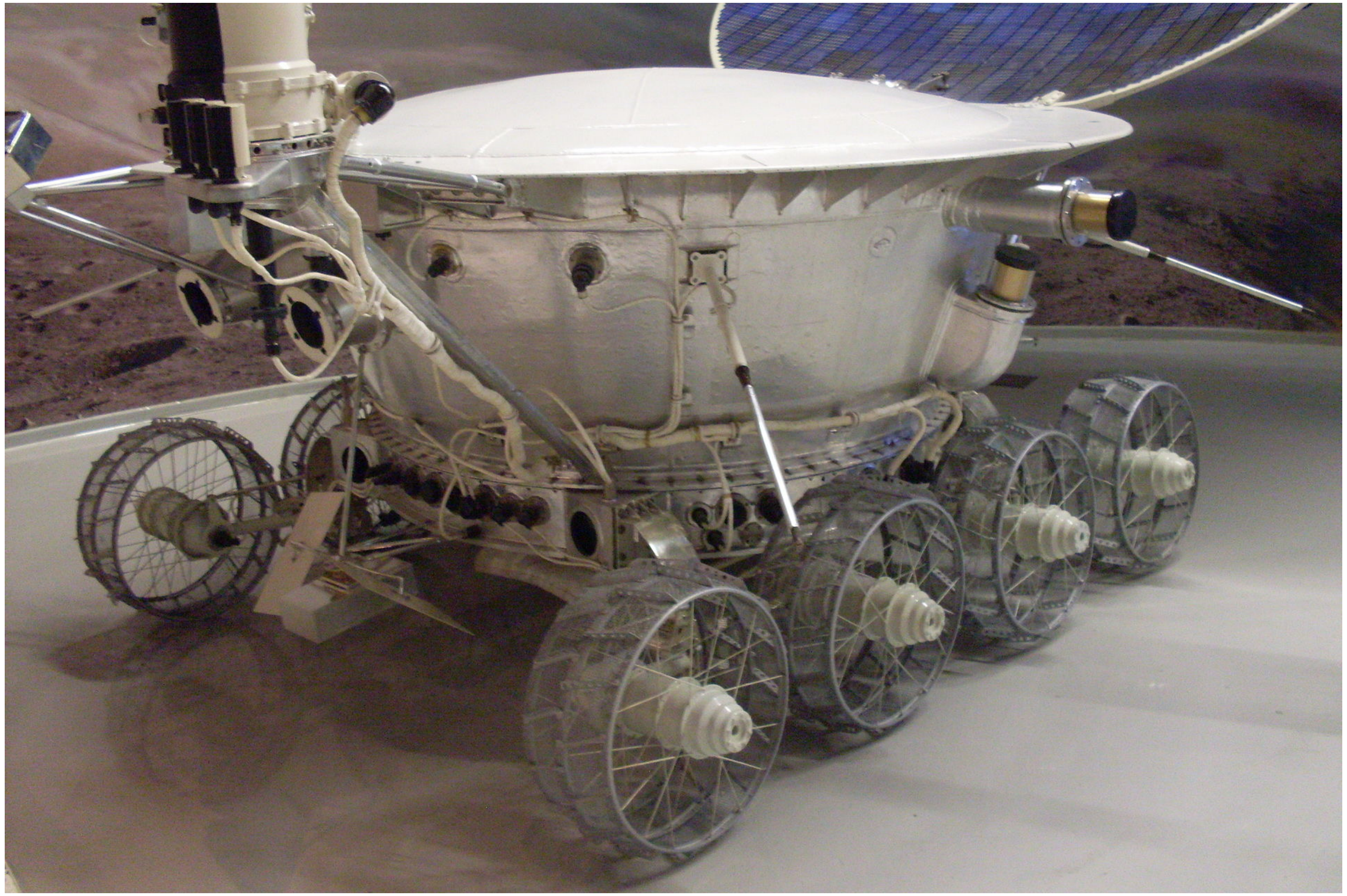

KEEP CLEAR

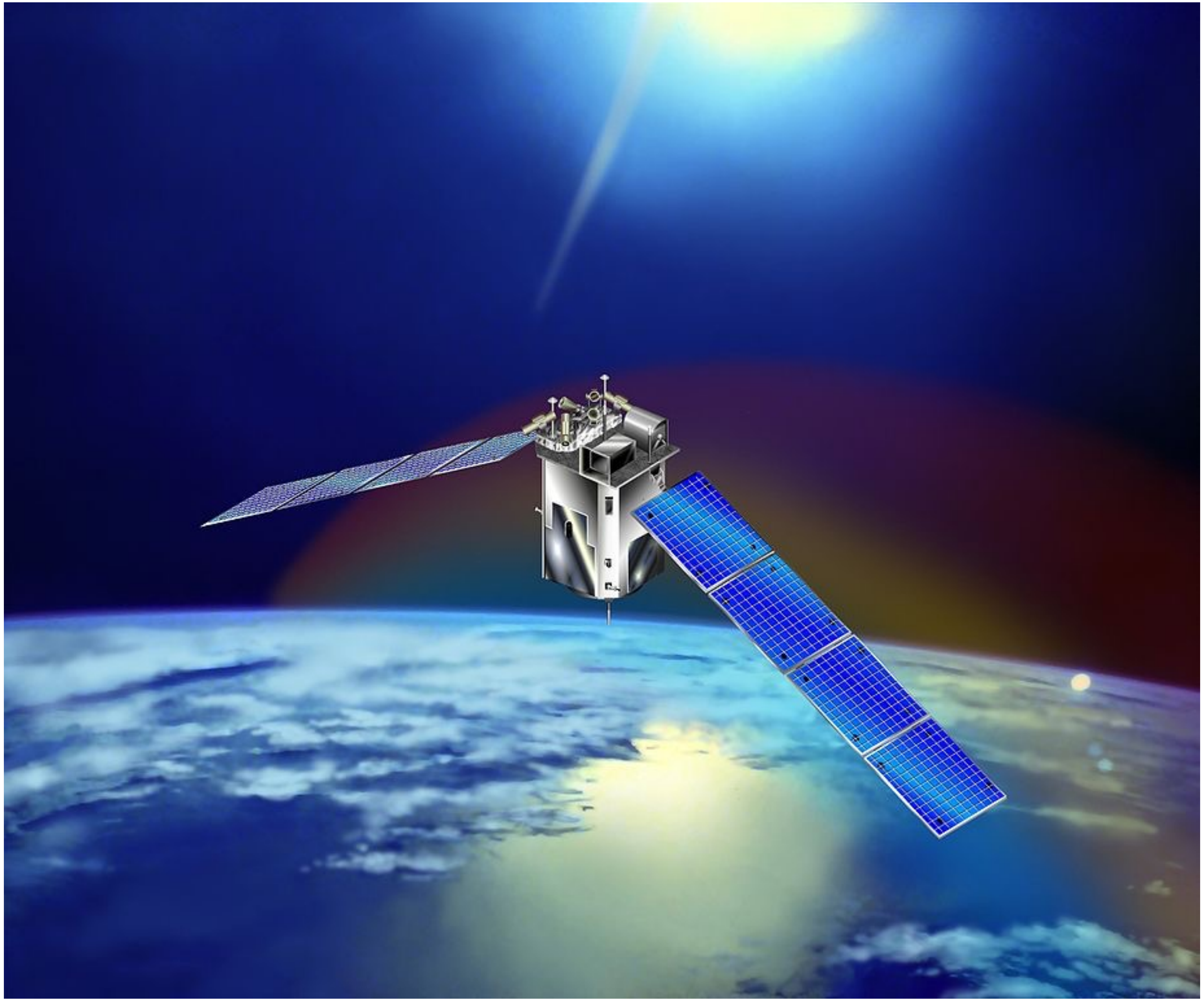

iRobot
Roomba
Robotic FloorVac
S
M
L
Select Room Size to Start / Stop


Robotics Technology
Development and Commercialization
Unmanned Vehicle
Systems Engineering
Navigation Systems



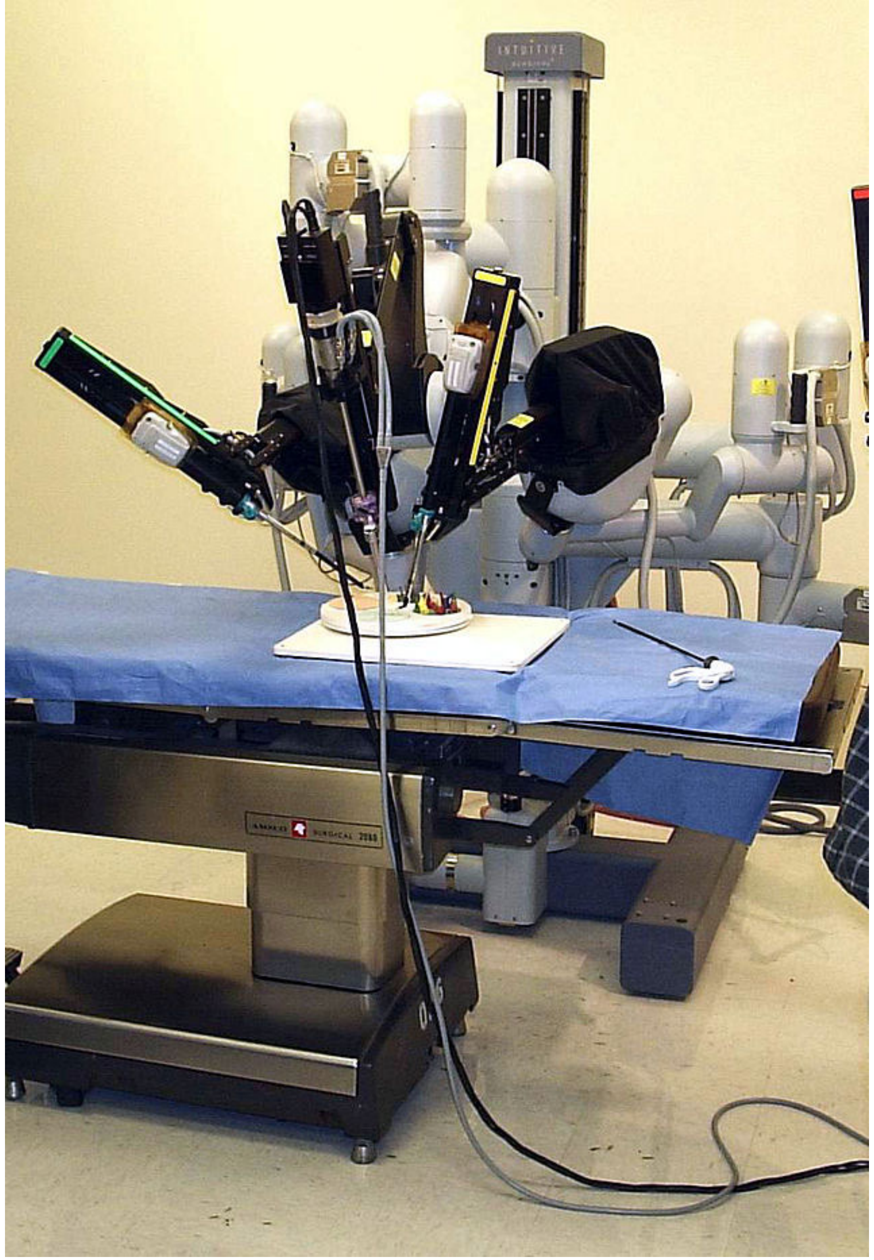

U.S. AIR FORCE
GLOBAL HAWK
HIGH ALTITUDE LONG ENDURANCE
UNMANNED AERIAL VEHICLE SYSTEM
Full Scale Mock-up
NORTHROP GRUMMAN



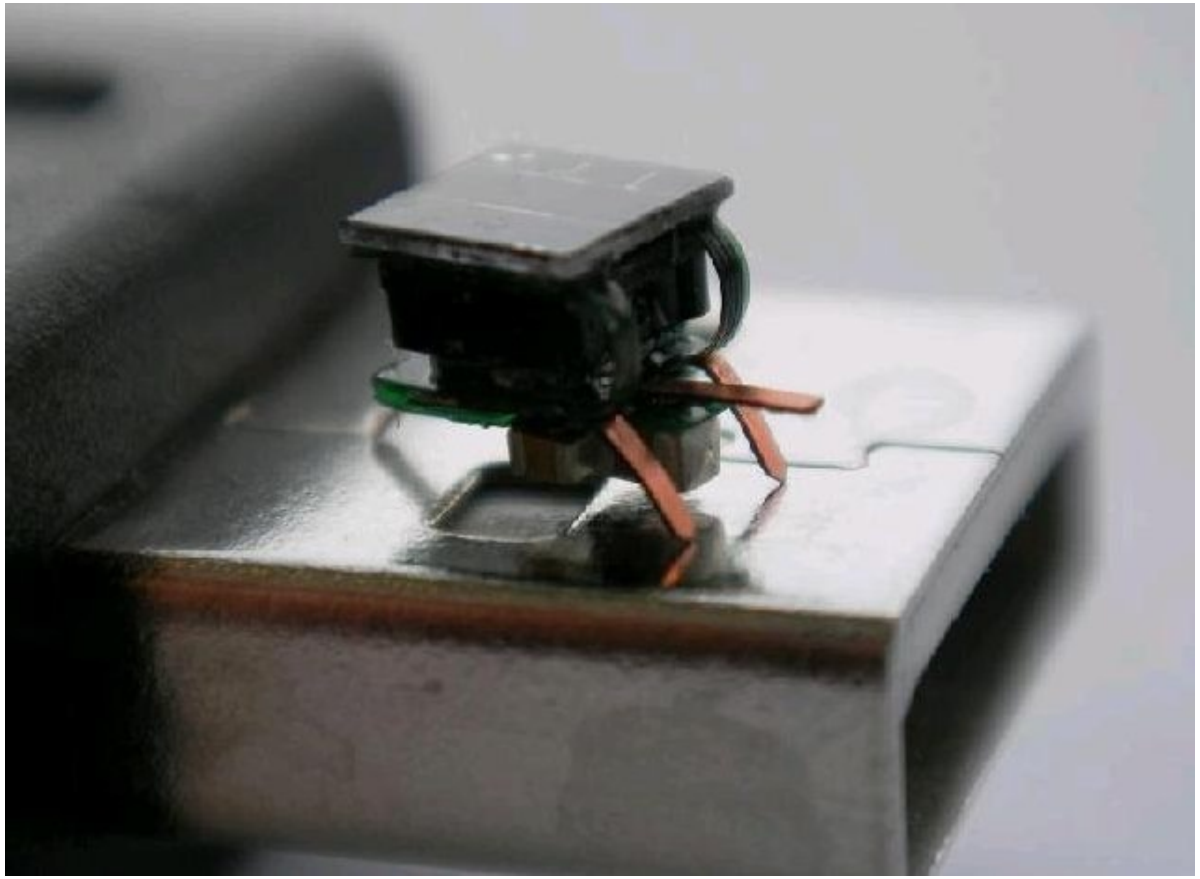


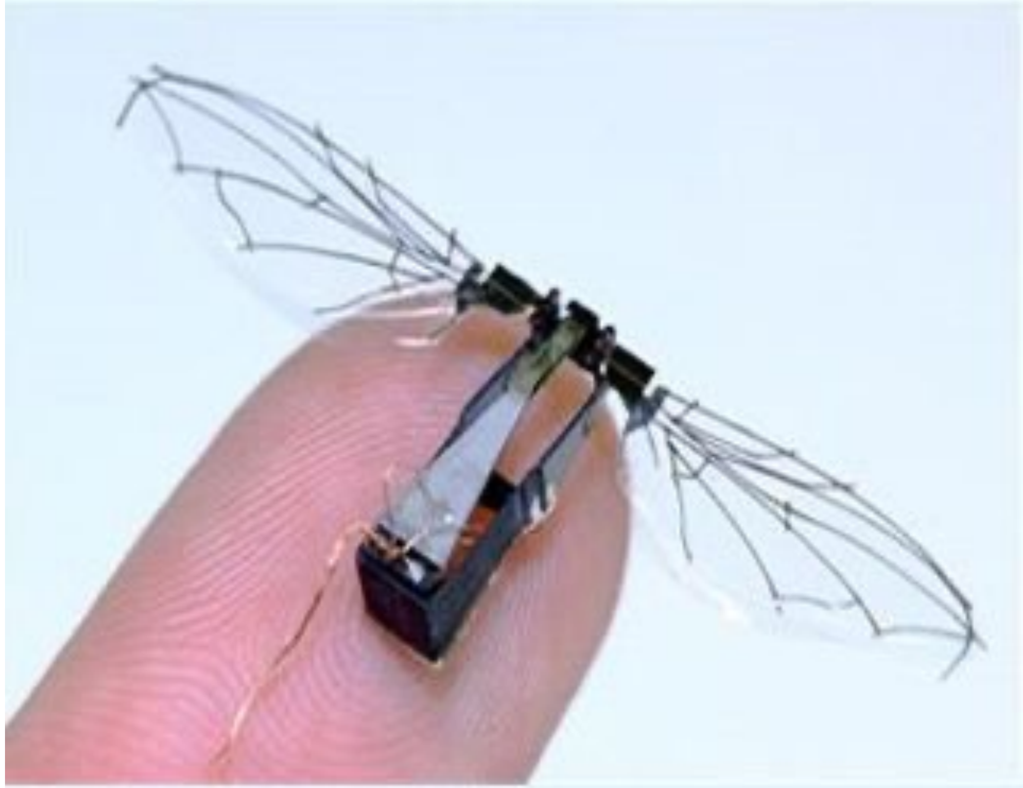

EXPLOSIVE


JASON
WOODS HOLE
OCEANOGRAPHIC INSTITUTION


INTUITIVE


P
Electric vehicle
recharging point
only
At any
time
TESLA
TESLA
Electric vehicle
recharging point
only
At any
time
TESLA
TESLA
GB





Recent prototype of the Harvard Microrobotic Fly, a three-centimeter wingspan flapping-wing robot.

Image Credit: Ben Finio, The Harvard Microrobotics Lab

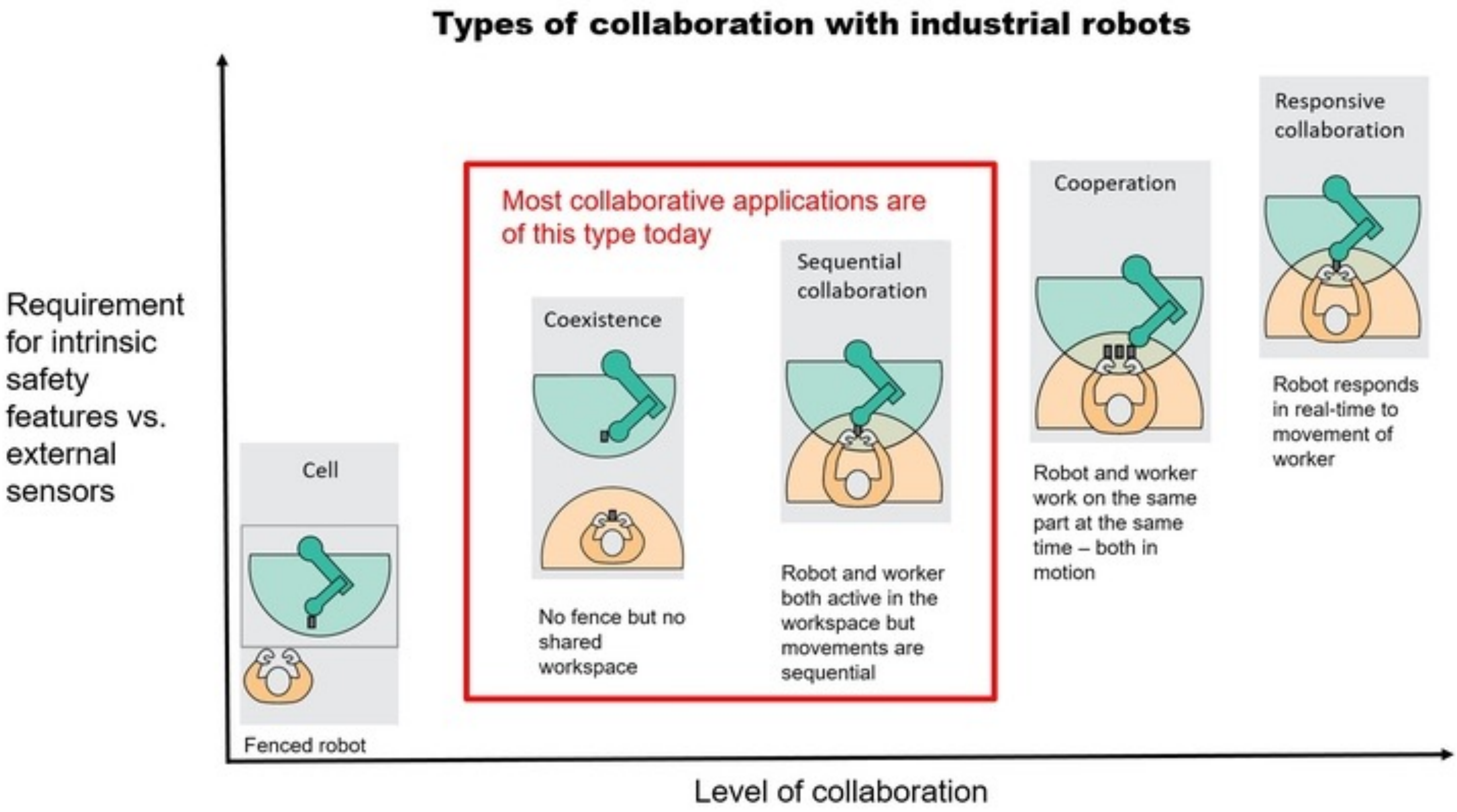

Daicd
3

Prof‘s Definition: A Robot is ...

A machine
capable of performing complex tasks
in the physical world,
that is using sensors to perceive the environment
and acts tele-operated or autonomous.

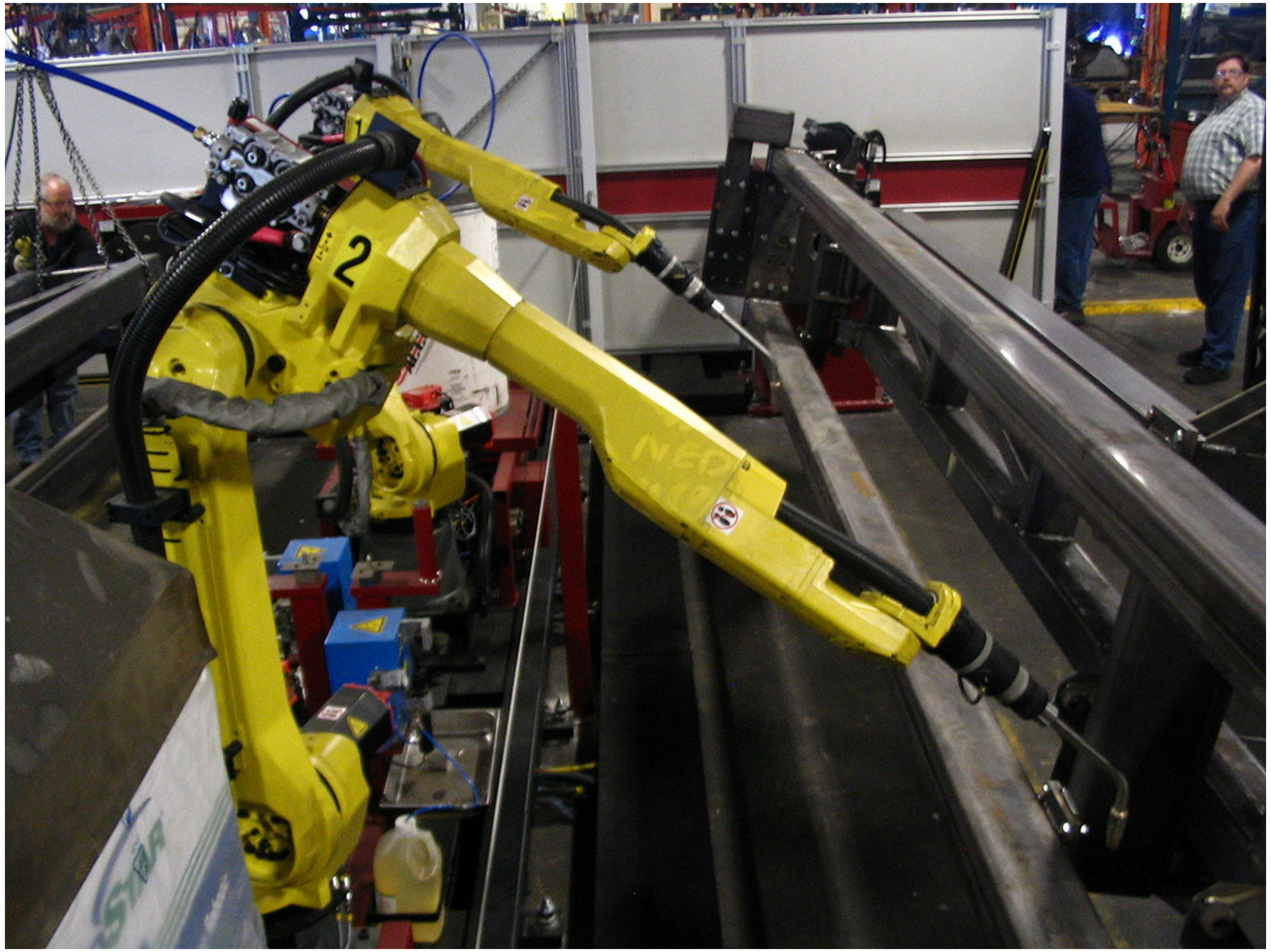
International Organization for Standardization: ISO 8373 Definition

- https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en
- Robot
  - actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks
- Industrial Robot
  - automatically controlled,
  - reprogrammable,
  - multipurpose
  - manipulator,
  - programmable in three or more axes
  - which can be either fixed in place or mobile for use in industrial automation applications
- Service Robot
  - robot that performs useful tasks for humans or equipment excluding industrial automation applications



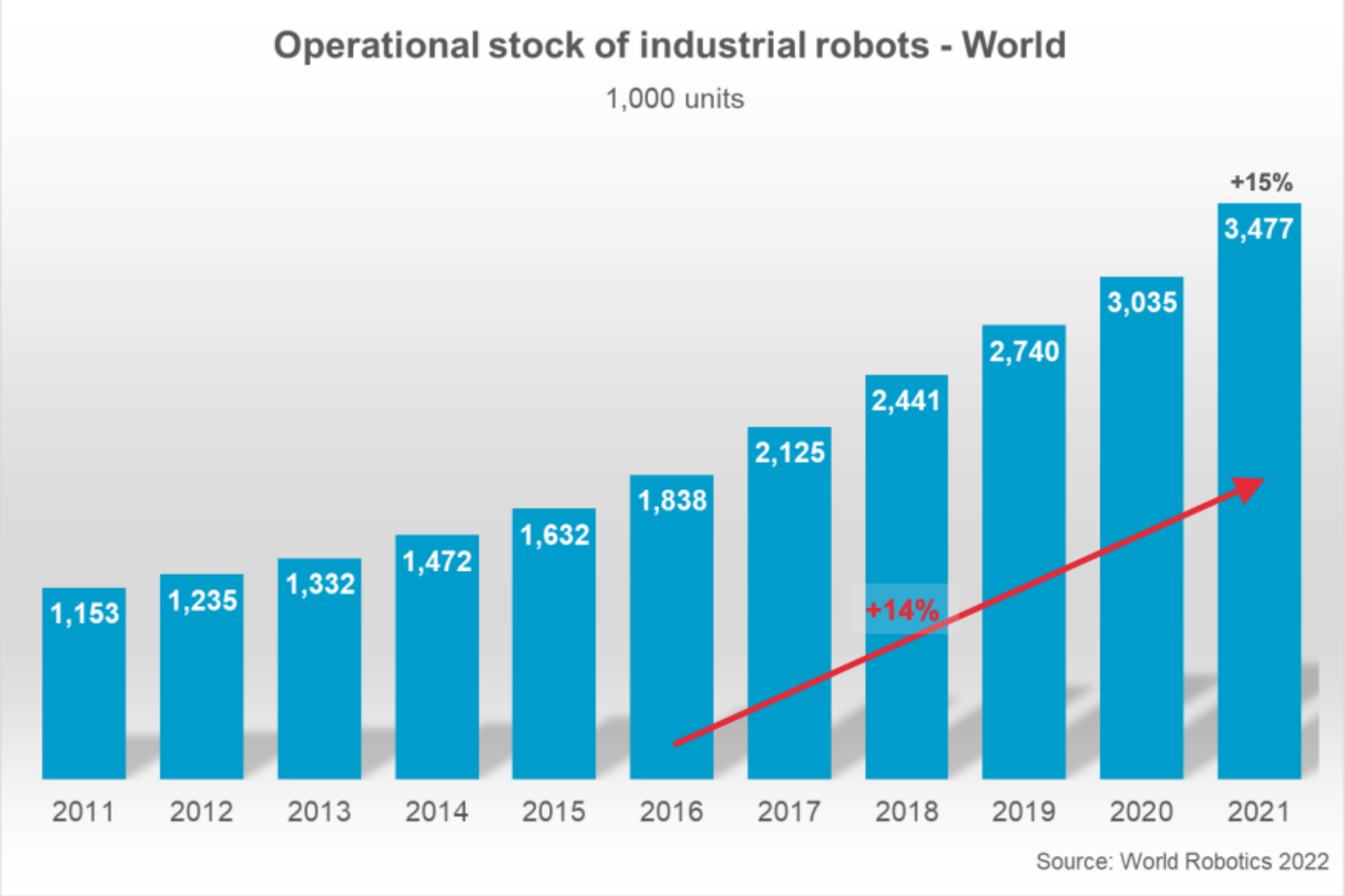
Green area: robot's workspace; yellow area: worker's workspace
Source: IFR (classification), adapted and modified from Bauer et al. (2016).

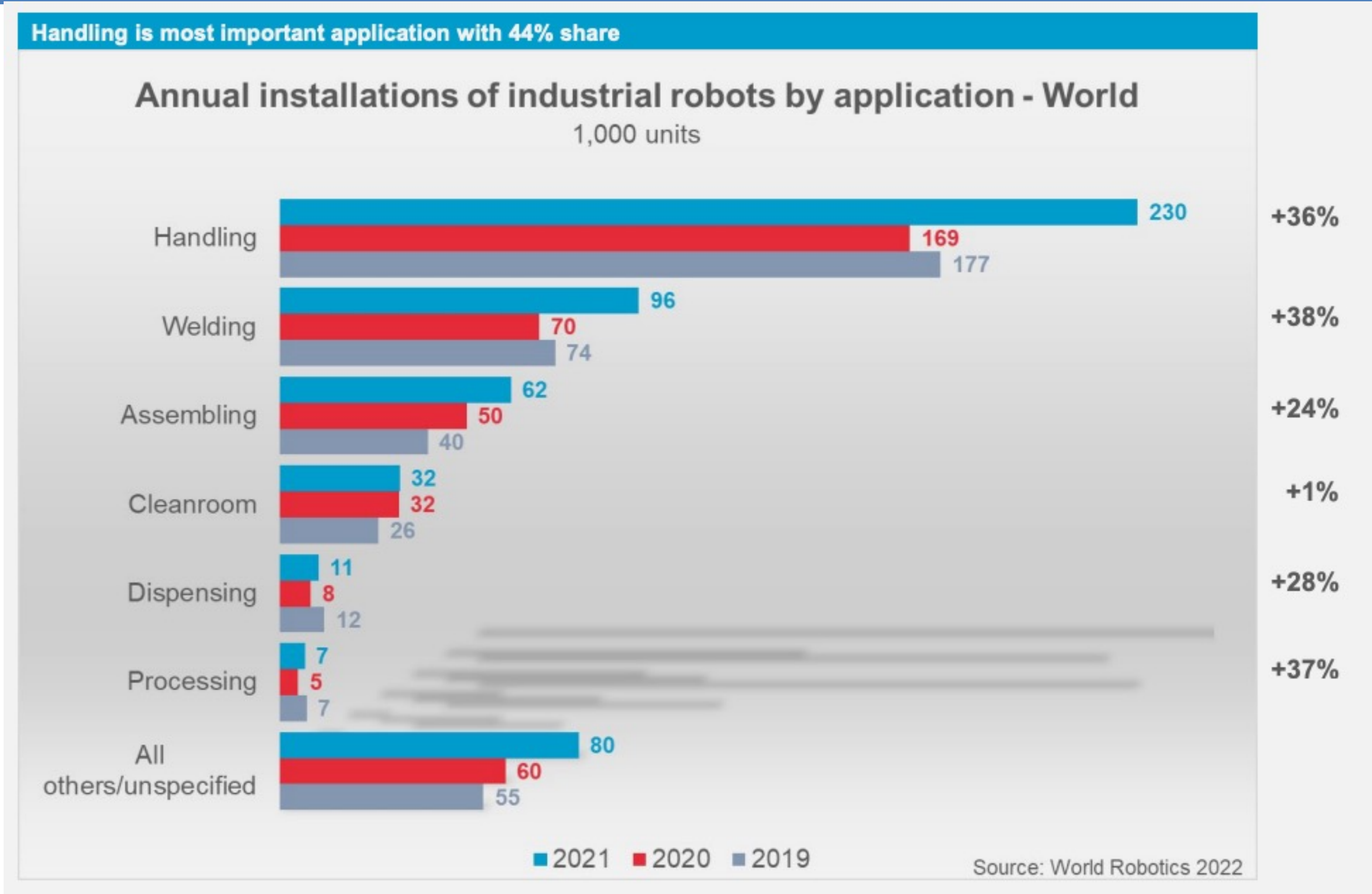
Industry vs Mobile Robots

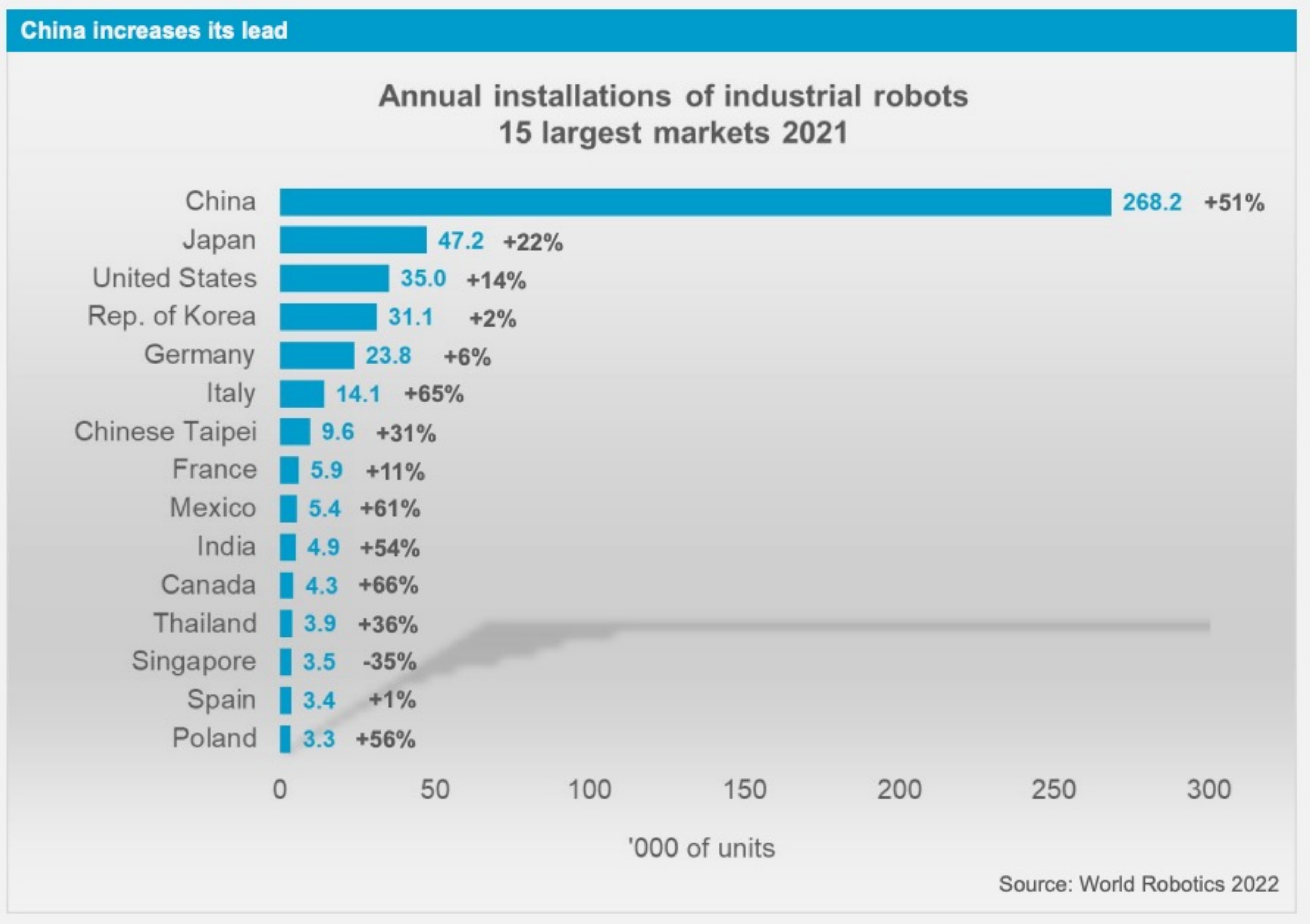


- Industrial Robots rule:
  - 2021: 3.5 million industrial robots installed
  - Over 0.5 million new robots that year!
  - China biggest robot market regarding annual sales - also fasted growing market worldwide
- Industrial Robots stay at one place!
- Almost all other robots move => **Mobile Robotics**

3 million industrial robots operating in factories around the world




Handling is most important application with 44% share
Annual installations of industrial robots by application - World
1,000 units
Handling
230
169
177
+36%
Welding
96
70
74
+38%
Assembling
62
50
40
+24%
Cleanroom
32
32
26
+1%
Dispensing
11
8
12
+28%
Processing
7
5
7
+37%
All others/unspecified
80
60
55
2021 2020 2019
Source: World Robotics 2022


China increases its lead
Annual installations of industrial robots
15 largest markets 2021
China 268.2 +51%
Japan 47.2 +22%
United States 35.0 +14%
Rep. of Korea 31.1 +2%
Germany 23.8 +6%
Italy 14.1 +65%
Chinese Taipei 9.6 +31%
France 5.9 +11%
Mexico 5.4 +61%
India 4.9 +54%
Canada 4.3 +66%
Thailand 3.9 +36%
Singapore 3.5 -35%
Spain 3.4 +1%
Poland 3.3 +56%
0 50 100 150 200 250 300
'000 of units
Source: World Robotics 2022

Why **Autonomous** Mobile Robotics?

- Tele-operating robots: boring and inefficient
- Autonomous robots: Robots that act by their own reasoning
  - Human operator might be present: Gives high level tasks
- Why autonomy?
  - Autonomous behaviors might be **better** than remote control by humans
  - Remote control might be **boring** or **stressful** and **tiresome**
  - Human operators might be a **scarce** resource or **expensive**
  - Multi robot approaches: One operator for many robots
- Semi-autonomy:
  - Autonomous behaviors that help the operator, for example:
  - Way-point navigation, autonomous stair climbing, assisted manipulation
  - Gradual development from tele-operation to full autonomy possible

- Autonomous mobile robots move around in the environment. Therefore **ALL** of them:
  - They need to know **where** they **are**.
  - They need to know **where** their **goal** is.
  - They need to know **how** to get there.

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- Where am I?
  - Global Positioning System: outdoor, error measured in meters
  - Guiding system: (painted lines, inductive guides), markers, iBeacon
  - Model of the environment:
    - Map, Localize yourself in this model
    - Mapping: Build the map while driving

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  - <u>They need to know **where** their **goal** is.</u>
  - They need to know **how** to get there.

- Where is my goal?
- Two part problem:
  - What is the goal?
    - Expressed using the world model (map)
    - Using object recognition
    - No specific goal (random)
  - Where is that goal?
    - Coordinates in the map
    - Localization step at the end of the object recognition process
    - User input

- Autonomous mobile robots move around in the environment. Therefore **ALL** of them:
  - They need to know **where** they **are**.
  - They need to know **where** their **goal** is.
  - They need to know **how** to get there.

- Different levels:
  - Control:
    - How much power to the motors to move in that direction, reach desired speed
  - Navigation:
    - Avoid obstacles
    - Classify the terrain in front of you
    - Follow a path
  - Planning:
    - Long distance path planning
    - What is the way, optimize for certain parameters

Most important capability

(for autonomous mobile robots)

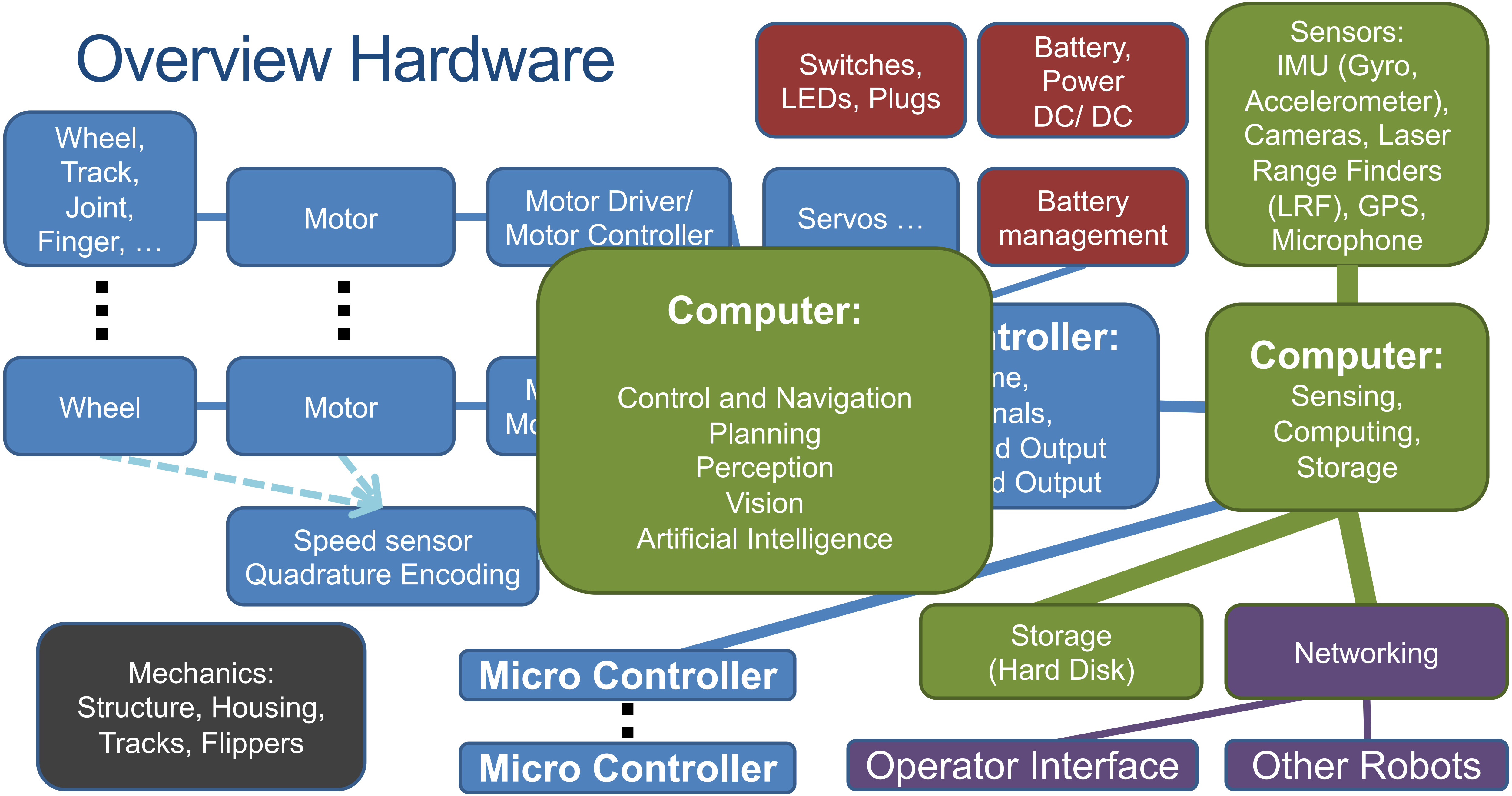
How to get from place A to place B?

(safely and efficiently)

How to get from A to B?

What are the components of a ROBOT?

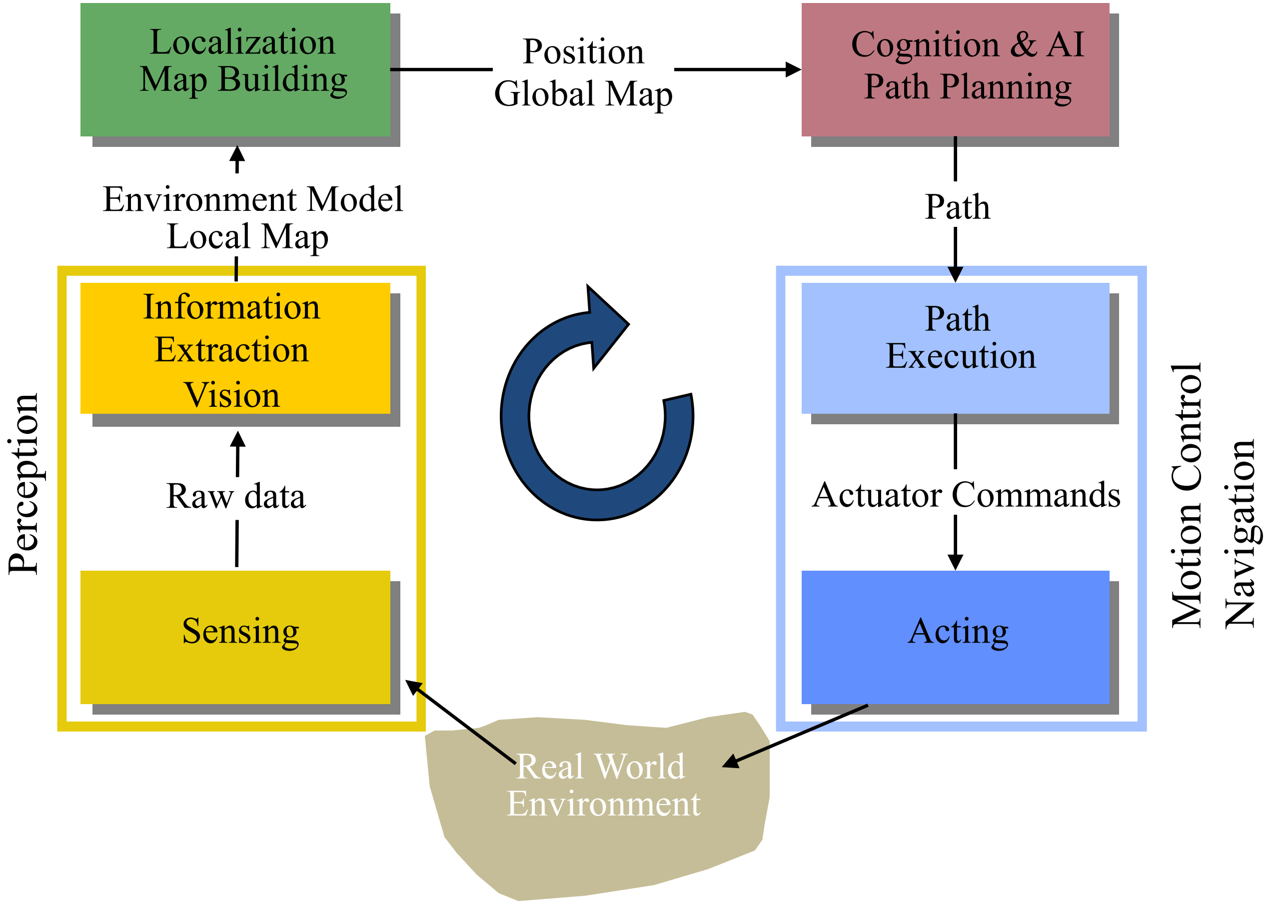
Overview Hardware



How to get from A to B?

How to program an intelligent ROBOT to go from A to B?

General Control Scheme for Mobile Robot Systems



ADMINISTRIVIA

Teaching Plan

- Lectures
- Homework
  - Including one real Hardware Group Project
- Presentation about robotics paper (related to your project)
- Midterm and Final Exams
- Project…

Course Contents

- Robotics CS283 is about
  - Algorithms and software for
  - Mobile robots
  - Especially w.r.t:
  - Perception
  - Mapping/ SLAM
  - Navigation/ Planning/ Control
  - Autonomy

- Mobile Manipulation CS289:
  - Emphasis on manipulation
  - CS283 has double the credit points for project – higher emphasis – more work – better results expected!

Project

- 2 credit points!
- Work in groups, min 2 students, max 3 students!
- Next lecture: Topics will be proposed…
  - You can also do your own topic, but only after approval of Prof. Schwertfeger
    - Prepare a short, written proposal till next Tuesday!

- Topic selection: in 1-2 weeks!
  - One member writes an email for the whole group to Yongqi: zhangyq12023 (at) shanghaitech.edu.cn ; Put the other group members on CC
  - Subject: [Robotics] Group Selection

- One graduate student from my group will co-supervise your project
- Weekly project meetings!

- Oral "exams" to evaluate the contributions of each member
- No work on project => bad grade of fail

Grading

- Grading scheme is not 100% fixed
- Approximately:
  - Lecture: 50%
    - Quizzes during lecture (reading assignments): 4%
    - Homework: 18%
    - Midterm: 8%
    - Final: 20%
  - Project: 50%
    - Paper Presentation: 5%
    - Project Proposal: 5%
    - Intermediate Report: 5%
    - Weekly project meetings: 10%
    - Final Report: 10%
    - Final Demo: 10%
    - Final Webpage: 5%

Getting Help

- Piazza:
  - For discussions and announcements
  - https://piazza.com/shanghaitech.edu.cn/spring2025/cs283/home
  - Ask questions regarding your reading assignments and homework
  - You are not allowed to give the solutions – just guidance
- Ask questions during the lecture!
- Upon request we can organize a tutorial session
- Only if everything else fails: write e-mails
- Office Hours Prof. Schwertfeger: Tuesday afternoon
- Office Hours TA Yongqi Zhang: make appointment via email

Policy on Plagiarism

- The homework are individual tasks!
- You may discuss the ideas and algorithms of homework with others but:
  - At no time should you read the source code or possess the source files of any other person, including people outside this course.
  - We will **detect plagiarism** using automated tools and will **prosecute** all violations to the fullest extent of the university regulations, including failing this course, academic probation, and expulsion from the university.

- Homework, project submissions, etc. will be submitted through git – using gitlab. You will get accounts on:
  - https://robotics.shanghaitech.edu.cn/gitlab

Mobile Robotics

- Topic Robots and how to program them:
  - Applications of robotics, software design, locomotion, hardware, sensing, localization, motion planning, autonomy for mobile robots, manipulation

- **Literature:**
- Mobile Robotics Mathematics, Models, and Methods
  - Alonzo Kelly
  - ISBN 978-1-107-03115-9
- Introduction to Autonomous Mobile Robots
  - Roland Siegwart, Illah R. Nourbakhsh, Davide Scaramuzza
  - ISBN: 978-0-262-01535-6

Material

- Webpage
  - https://robotics.shanghaitech.edu.cn/teaching/robotics2025
  - Slides will be available on the webpage
- Piazza
  - https://piazza.com/shanghaitech.edu.cn/spring2025/cs283/home
- Where to find us:
  Office: SIST 1D 201.A
  Lab: SIST 1D 203
- E-Mail:
  - soerensch@ShanghaiTech.edu.cn
- Wechat group: >>>>>>>>>

Group: CS283
Robotics 2025

Prerequisite: Robot Operating System 2 !

- Program in C++ (or python) and ROS 2 (https://docs.ros.org/)

- Recommended: Operating System Ubuntu Linux (www.ubuntu.com)
  - **Recommended option:** Dual boot on your own Laptop/ Computer – needs min. 40 GB from HD
  - Virtual Machine will perform poorly for some HW requiring to run a robot simulator

- ROS 2 version: We strongly suggest Jazzy or Iron – with Ubuntu 24.04 or 22.04

- ROS 2 also supports Windows and MacOS – but we will not offer any help/ user support for these – use at your own risk – Ubuntu/ Linux is suggested!
  - Certain libraries (e.g. pcl) are Linux only on ROS 2

- Other tools: git, LaTeX, …

Schedule

- May change – always check on webpage for most recent version!

	Classes	Project	Class Topic	Project Activity	HW
2025-02-18	1		Introduction		
2025-02-20	2		Kinematics		
2025-02-25	3		Sensors 1		**HW 1 due**
2025-02-27	4		Sensors 2 & Hough Transform		
2025-03-04	5		Perception		
2025-03-06	6		Maps & Map Rep. & Signed Dist.	1st Project meeting	
2025-03-11		1			
2025-03-13		2		**Project Proposal Due**	
2025-03-18		3			
2025-03-20	7		ICP	2nd Project meeting	**HW 2 due**
2025-03-25	8		Localization		
2025-03-27	9		SLAM I		
2025-04-01	10		SLAM II		
2025-04-03	11		Planning	3rd Project Meeting	**HW 3 due**
2025-04-08		4		**Paper Presentations**	
2025-04-10		5		**Paper Presentations**	
2025-04-15		6		**Paper Presentations**	
2025-04-17	12		**Midterm**		
2025-04-22	13		Vision I		
2025-04-24	14		Vision II		
2025-04-29		7		4th Project meeting	**HW 4 due**
2025-05-01		8	**Labor day**		
2025-05-06	15		PID; PWM; (gears); Electronics		
2025-05-08	16		DL & Ethics	**Project Intermediate Report Due**	
2025-05-13	17		Reinforcement Learning	5th Project meeting	
2025-05-15		9			
2025-05-20		10			
2025-05-22		11			**HW 5 due**
2025-05-27		12		6th Project meeting	
2025-05-29		13			
2025-06-03		14			
2025-06-05		15		8th Project meeting	
2025-06-10		16			
2025-06-12			**Final**		
2025-06-17					
2025-06-19				**Demo; Webpage; Final Report Due**	

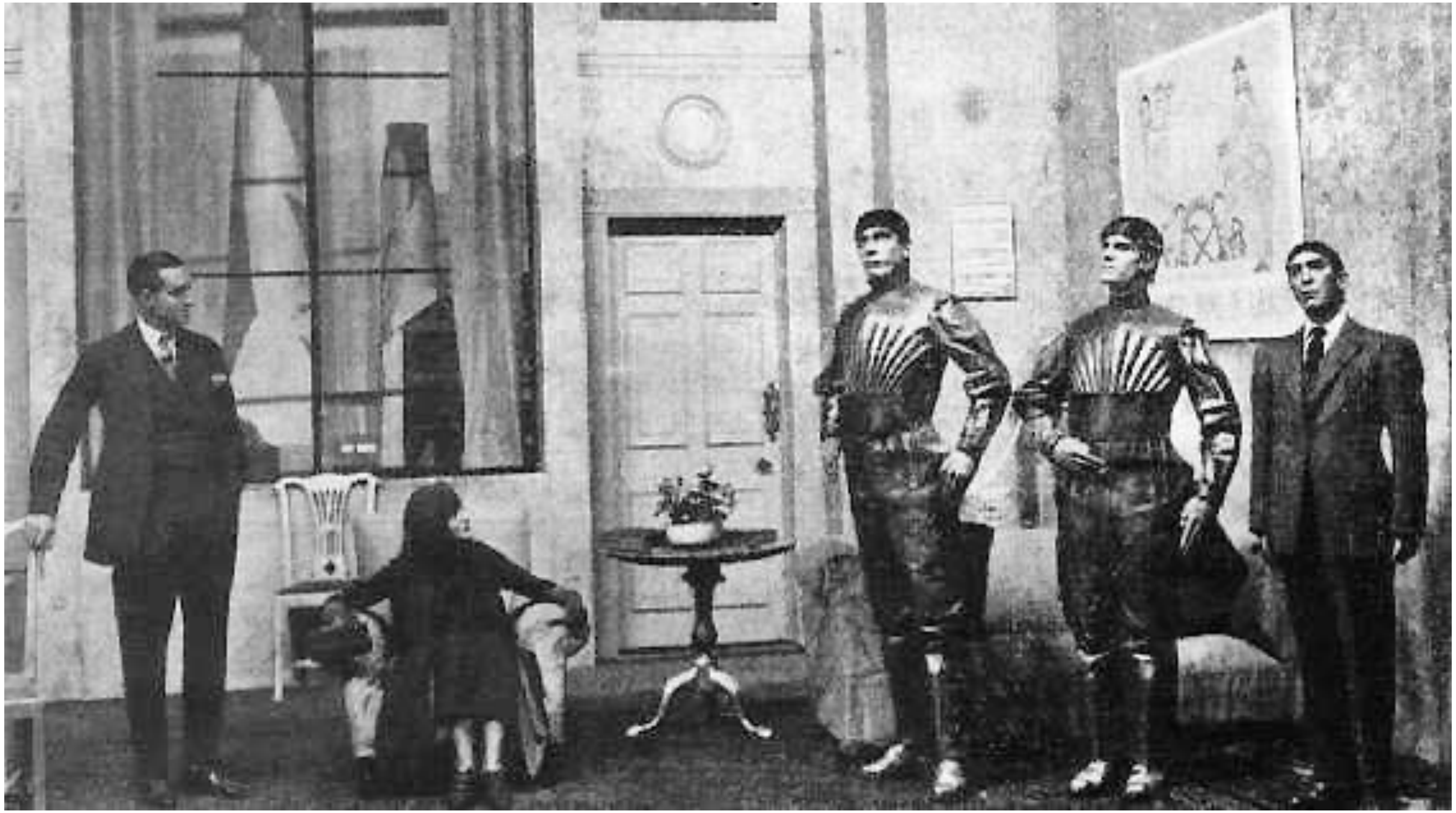
For this week

- Join the lecture on piazza
- Organize access to the two text books
- Do HW1: due Friday, Feb 28, 23:59
  - For the dual-boot installation of Ubuntu:
    - Backup your all your data
    - Free enough space (40 GB)
    - Download Ubuntu

BRIEF HISTORY

Brief History

Robota “forced labor”: Czech, Karel Čapek R.U.R. 'Rossum's Universal Robots' (1920).



Isaac Asimov - Three Laws of Robotics (1942)

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.

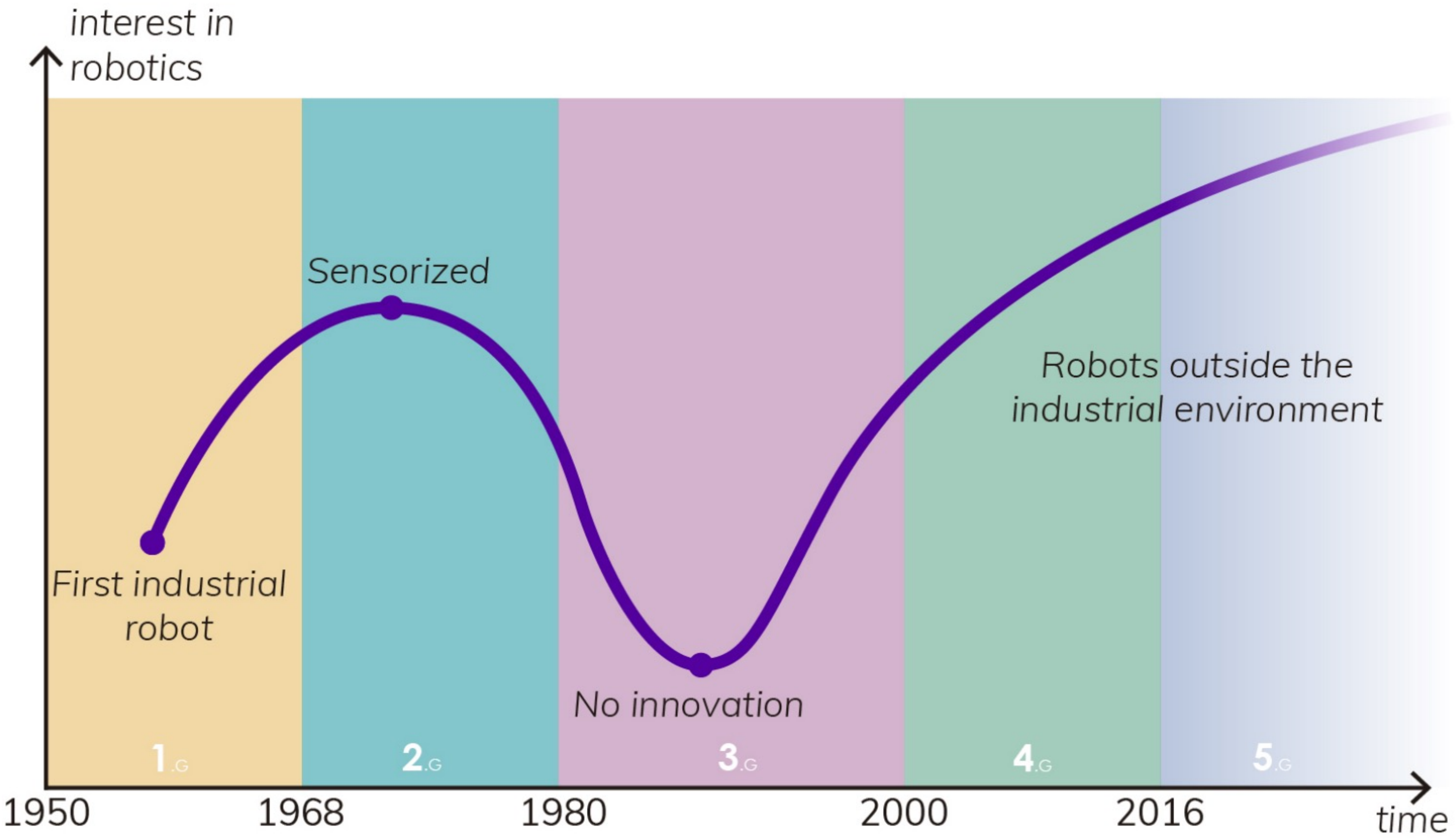
2. A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.

3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

0. A robot may not harm humanity, or, by inaction, allow humanity to come to harm.

History

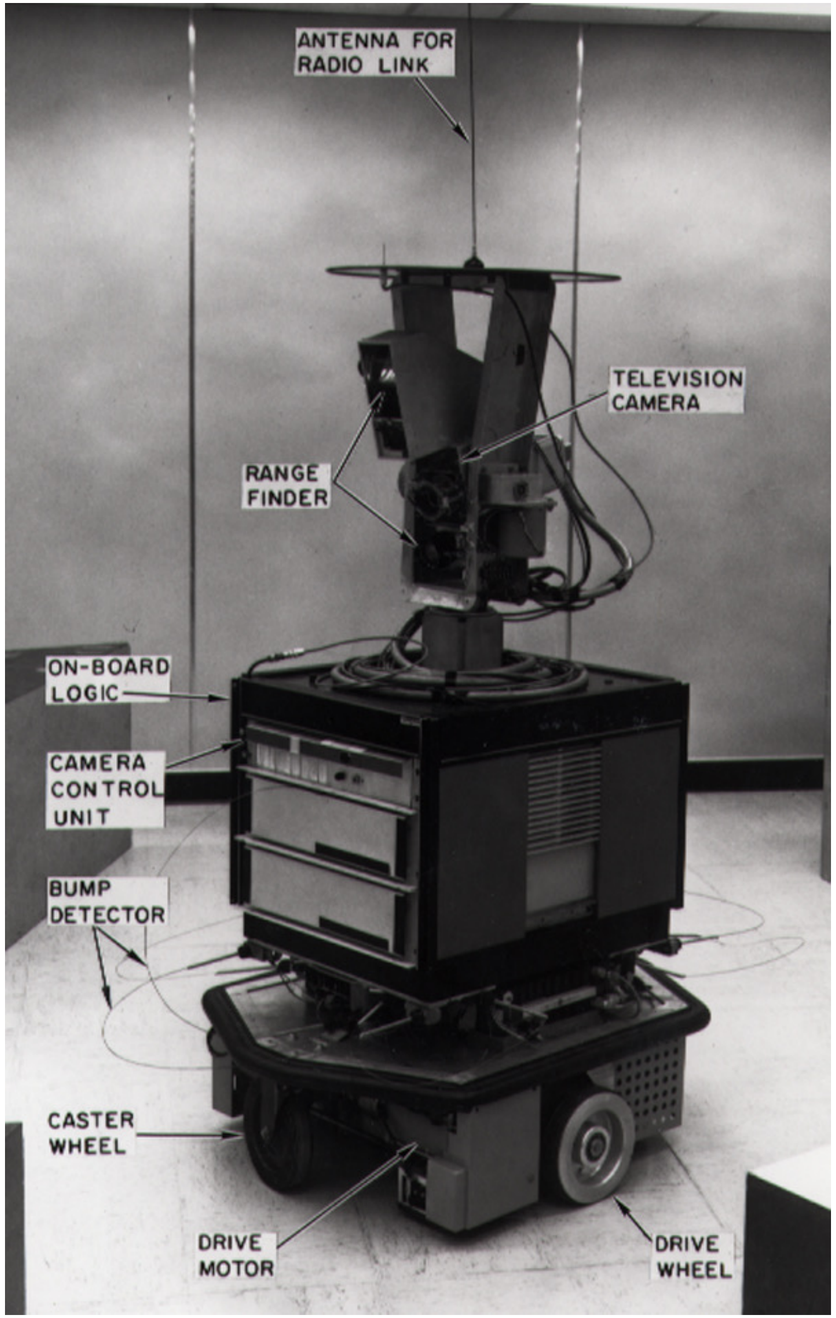
- First electronic autonomous robots 1949 in England (William Grey Walter, Burden Neurological Institute at Bristol)
  - three-wheeled robots: drive to recharging station using light source (phototaxis)
- Turing Test: 1950 (British mathematician Alan Turing)
- Unimate: 1961 lift hot pieces of metal from a die casting machine and stack them. First industry robot. Inventor: George Devol, user: General Motors.
- Lunokhod 1: 1970, lunar vehicle on the moon (Soviet Union)
- Shakey the robot: 1970
- 1989: Chess programs from Carnegie Mellon University defeat chess masters
- Aibo: 1999 Sony Robot Dog
- ASIMO: 2000 Honda (humanoid robot)



https://arxiv.org/pdf/1704.08617.pdf

Shakey the robot (1970)

- First general-purpose mobile robot to be able to reason about its own actions
- Advanced hardware:
  - radio communication
  - sonar range finders
  - television camera
  - on-board processors
  - bump detectors
- Advanced software:
  - Sensing and reasoning
- Very big impact
- https://robotics.shanghaitech.edu.cn/static/videos/Shakey.mp4



SOFTWARE

Robot Software: Tasks/ Modules/ Programs (ROS: node)

Support

- Communication with Micro controller
- Sensor drivers
- Networking
  - With other PCs, other Robots, Operators
- Data storage
  - Store all data for offline processing and simulation and testing
- Monitoring/ Watchdog

Robotics

- Control
- Navigation
- Planning
- Sensor data processing
  - e.g. Stereo processing, Image rectification
- Mapping
- Localization
- Object Recognition
- Mission Execution
- Task specific computing, e.g.:
  - View planning, Victim search, Planning for robot arm, …

Software Design

- Modularization:
  - Keep different software components separated
  - ☺ Keep complexity low
  - ☺ Easily exchange a component (with a different, better algorithm)
  - ☺ Easily exchange multiple components with simulation
  - ☺ Easily exchange dada from components with replay from hard disk instead of live sensor data
  - ☺ Multiple programming teams working on different components easier
  - Need: Clean definition of interfaces or exchange messages!
  - Allows: Multi-Process (vs. Single-Process, Multi-Thread) robot software system
  - Allows: Distributing computation over multiple computers

ROS 1 vs ROS 2

- ROS 1 developed since 2007 – but end of life scheduled for 2025
- ROS 2 developed since 2015
- Advantages/ changes ROS 2:
  - Supports more OS's (Windows, MacOS)
  - Core written in C, bindings (e.g. C++, python) more consistent
  - Modern C++ interface (C++11, C++17)
  - OOP kind of enforced (code quality)
  - ROS2 Components (similar to ROS1 nodelets) enforced -> more performant intra-process communication
  - Communication via DDS (Data Distribution Service) – no more ROS master – better, following industry standards
  - Quality of Service (QoS) for communication (e.g. accept lost messages)
  - More modern build system (Ament instead of catkin)
  - Ros1 bridge: have a system run ROS1 and ROS2 with communication between nodes … (as a "hack" for the transition)

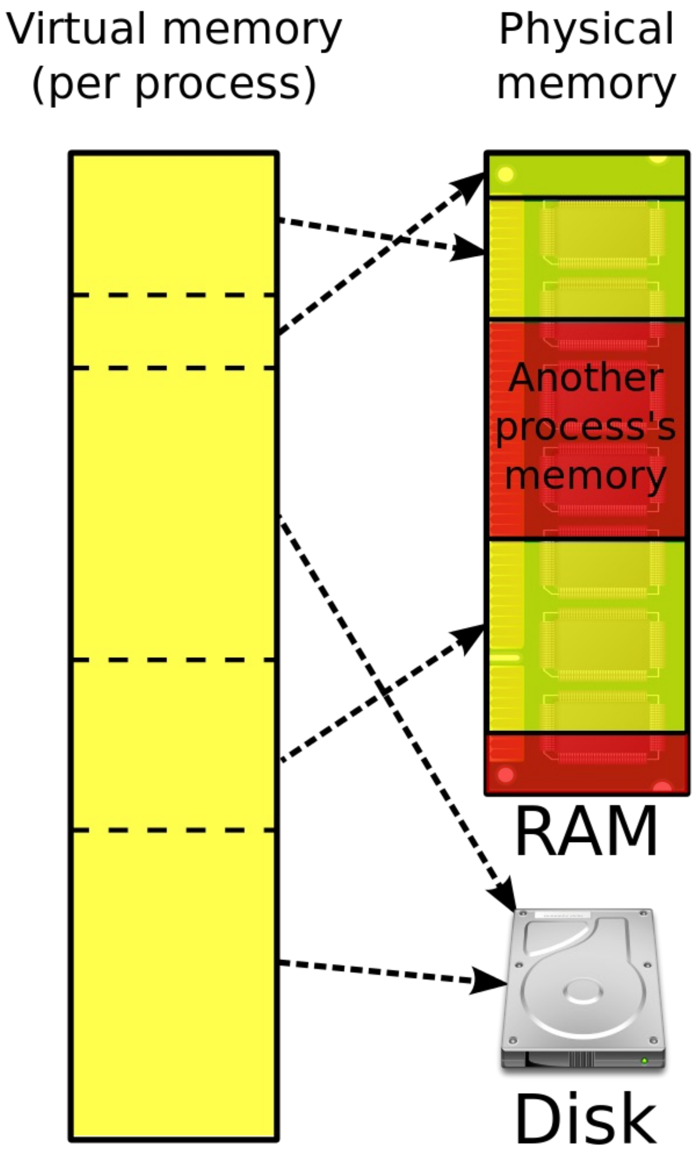
Programming review

- Process vs. Thread
- C++ Object Orientation
- Constant Variables
  - const-correctness
- C++ Templates
- Shared Pointer

- Objective:
  - Prerequisites for understanding ROS.
  - Understand how we can efficiently retrieve and transfer data in ROS.

Process

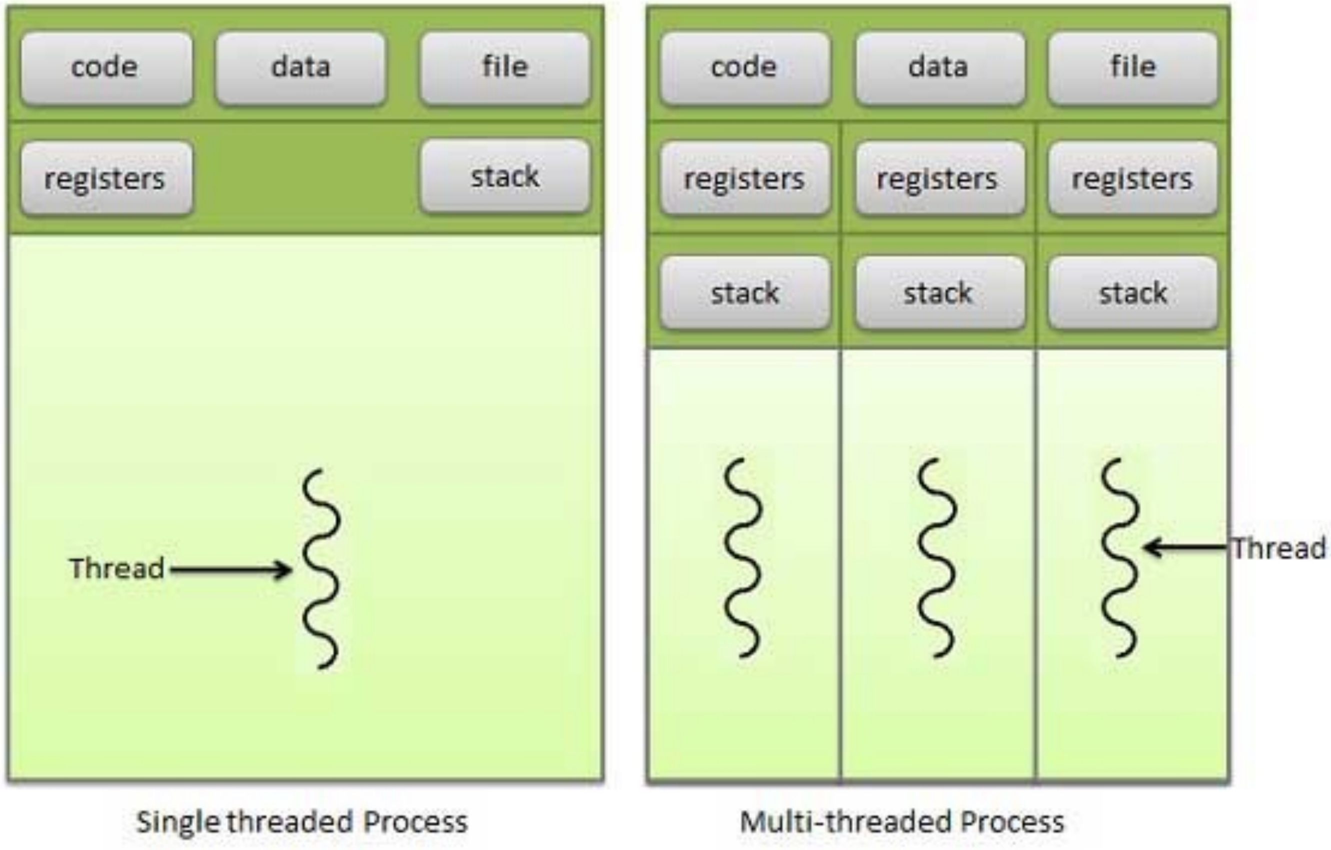
- Execution of one instance of a computer program
- Virtual memory:
  - Contains only code and data from this program, the libraries and the operating system
  - Other processes (programs) can not access this memory (shared memory access is possible but complicated)
- Operating system gives each process equal amount of processing time (scheduling) – if the processes need it
  - Good support from the operating system to give certain processes higher or lower priority
  - Linux console program to see processes: **top**



(From Wikipedia)

Multi-Threading

- In one process, multiple threads => parallel execution
- ☺ Code and Memory is shared => easy exchange of data, save mem.
- 😐 Synchronization can be tricky (mutex, dead lock, race condition)
- ☹ If one thread crashes, the whole process (all threads) die



(from http://www.tutorialspoint.com)

Processes and Threads in Robotics - Messages

- Robot Operating System (ROS): Multiple Processes:
  - Each component runs in its own process: called **node**
  - A node can have multiple threads => faster computation
  - Nodes communicate using **messages**
  - A node can send (**publish**) **messages** under different names called **topic**
  - Nodes can listen to (**subscribe**) **messages** under different **topics**
  - **messages** have a type (e.g. sensor_msgs/Image) – a **topic** can only have one **type**!
  - The messages are transferred over the network (TCP/IP) => multiple computers work together transparently
  - ☹ Messages are serialized, copied and de-serialized even if both nodes on the same computer => slow (compared to pointer passing)
    - Optimization: ROS 2 uses Component architecture: run different nodes in the SAME process => fast communication

C++ Templates

- Functions and classes that operate with generic types
- Function or class works on many different data types without rewrite
  - `template <typename T> int compare( T v1, T v2);`
  - Type of T is determined during compile time => errors during compilation (and not run-time)
  - Any type (type == class) that offers the needed methods & variables can be used
  - Usage: `compare<string>( string(“string number one”), “hello world” );`
    - Explicit declaration: typename T = string
    - typename T can (most often) deducted by the compiler from the argument types
- Class template:

```
template <typename T> class myStuff{
     T v1, v2;
     myStuff(T var1, T var2){  v1 = var2; v2 = var2; }
};
```

Template example

```
//This example throws the following error : call of overloaded 'max(double, double)' is ambiguous
template <typename Type>
Type max(Type a, Type b) {
    return a > b ? a : b;
}
```

```
#include <iostream>

int main(int, char**)
{
  // This will call max <int> (by argument deduction)
  std::cout << max(3, 7) << std::endl;
  // This will call max<double> (by argument deduction)
  std::cout << max(3.0, 7.0) << std::endl;
  // This type is ambiguous, so explicitly instantiate max<double>
  std::cout << max<double>(3, 7.0) << std::endl;
  return 0;
}
```

Constant Variables

- Declare variables that do not change (anymore) in the code: `const`
- Works for variables and objects
- Const Objects:
  - Only methods that do not change any variable of the object may be called =>
  - Those methods have to be declared const
- Used for program-correctness
- Especially for multi-threading:
  - Share the data (e.g. image)
  - Make it read only via const
  - => no side-effects between different threads

1. const int x = 5; // x may not be changed
2. int * someValue = &x; // pointer – compilation error!!
3. const int * pointy = &x; // good
4. *pointy = 8; // error – pointing to const!
5. int y = 4;
6. pointy = &y; // from non const to const is always possible!
7. const int * p2 const = &y; // pointing to const variable and p2 is also const
8. p2 =&x; // error – p2 is const

Shared Pointer

- C++ Standard Library (std): heavily templated part of C++ Standard (many parts used to be in boost library)
- Pointer: address of some data in the heap – in the virtual address space
- Space for data has to be allocated (reserved) with: `new`
- After usage of data it has to be destroyed to free the memory: `delete`
- Problem: Data (e.g.) image is shared among different modules/ components/ threads. Who is the last user – who has to delete the data?
  - Shared pointer: counts the number of users (smart pointers); upon destruction of last user (smart pointer) the object gets destroyed : called "Reference counting"
  - Problem: Shared pointer needs to know the destructor method for the pointer =>
  - Shared pointer is a templated class: Template argument: class type of the object pointed to
  - Shared pointer can also point to const object!