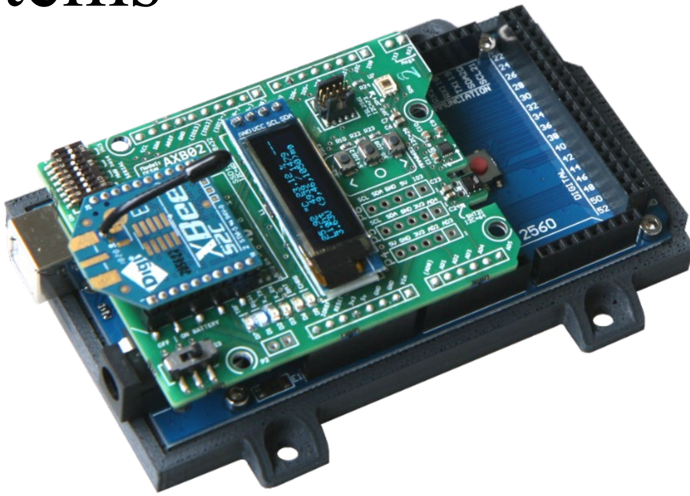
Signals, Instruments, and Systems – W8

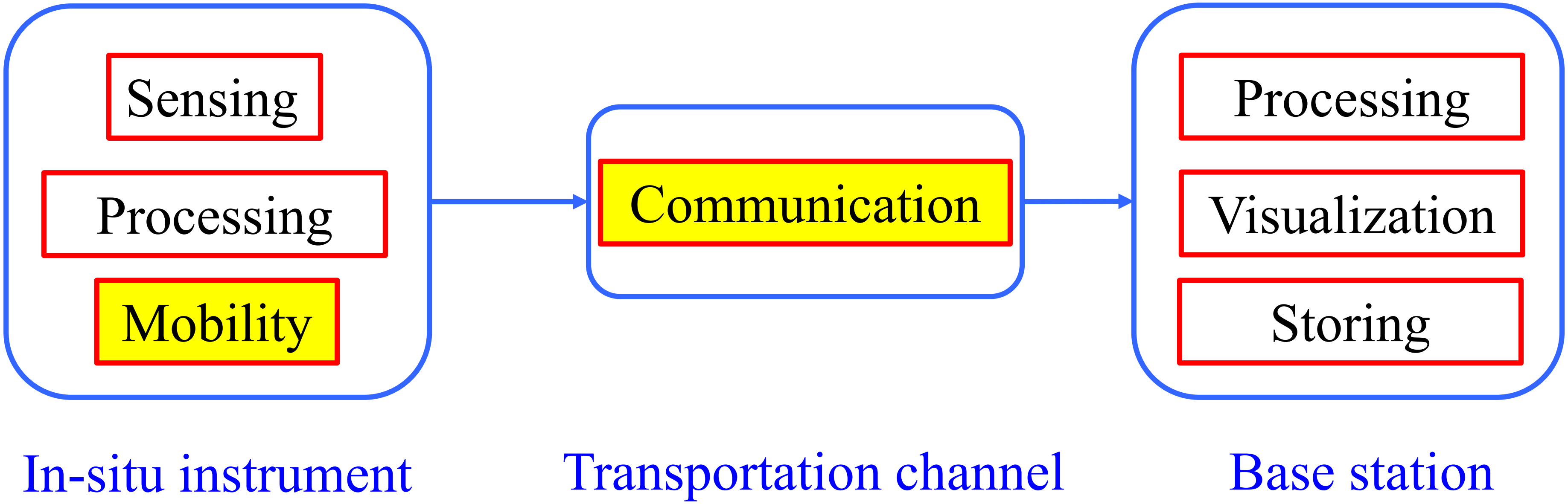
Introduction to Embedded Systems – Communication and Mobility

Outline

- Communication in embedded systems
  - Wired
  - Wireless
  - Power
- Mobility in embedded systems
  - Motivation, autonomy, and robots
  - Control architectures for mobile robots:
    - A simple taxonomy
    - The obstacle avoidance example



Motivation from Week 1 Lecture



Sensing

Processing

Mobility

Communication

Processing

Visualization

Storing

In-situ instrument

Transportation channel

Base station

Highlighted blocks are those mainly leveraging the content of this lecture.

Wired Communication

Where?

- Within embedded systems (from sensor to microcontroller, from microcontroller to microcontroller, etc.)
- From an embedded system to another
- From an embedded system to a PC
- …

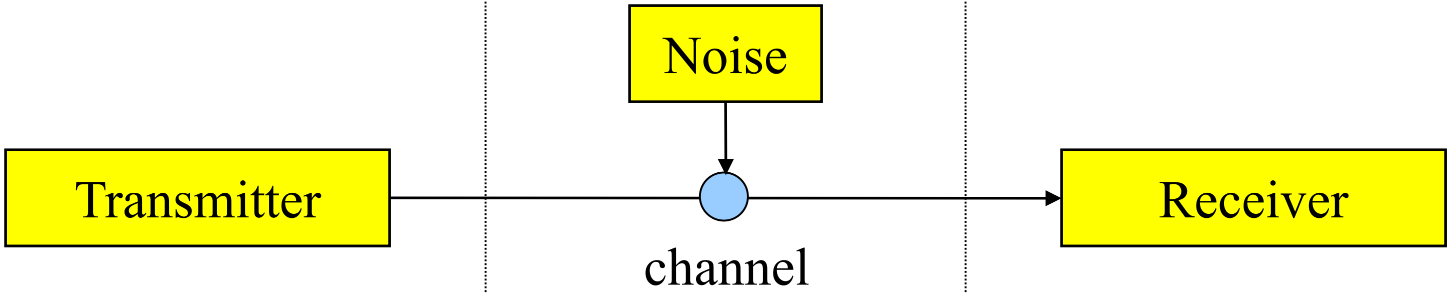
Communication Model


Transmitter

Receiver

channel

Communication Model



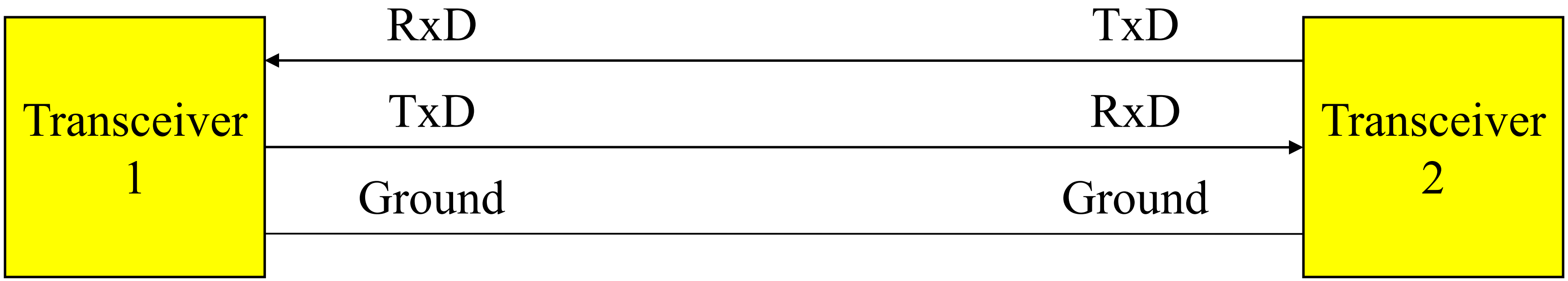
Modulation
Coding
(Compression)

Distortion
Filtering
Frequency shift
…

Demodulation
Decoding
(Decompression)

A Seminal Example: The RS-232 (serial port)

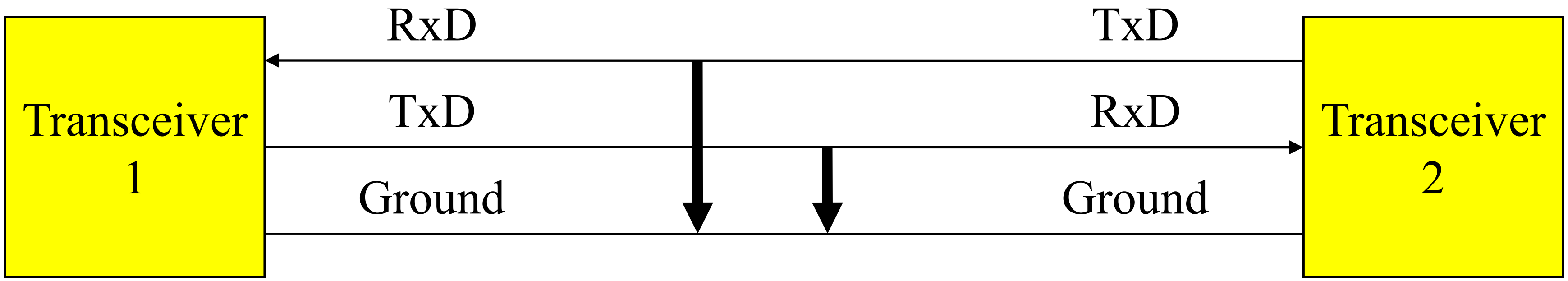
- Hardware:
  - 3 wires: TxD, RxD, Ground



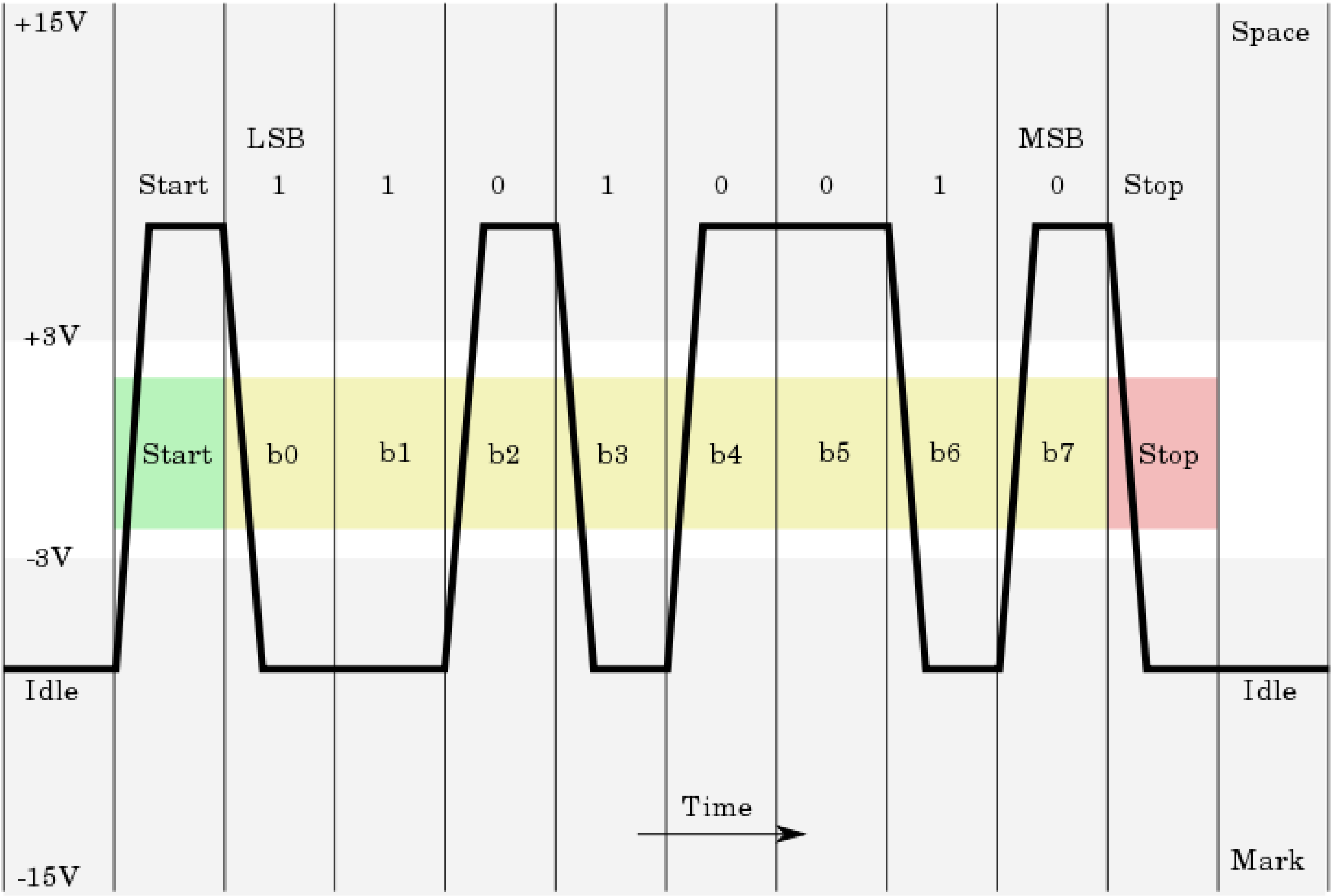
Transceiver = Transmitter + Receiver

RS-232 (serial port)

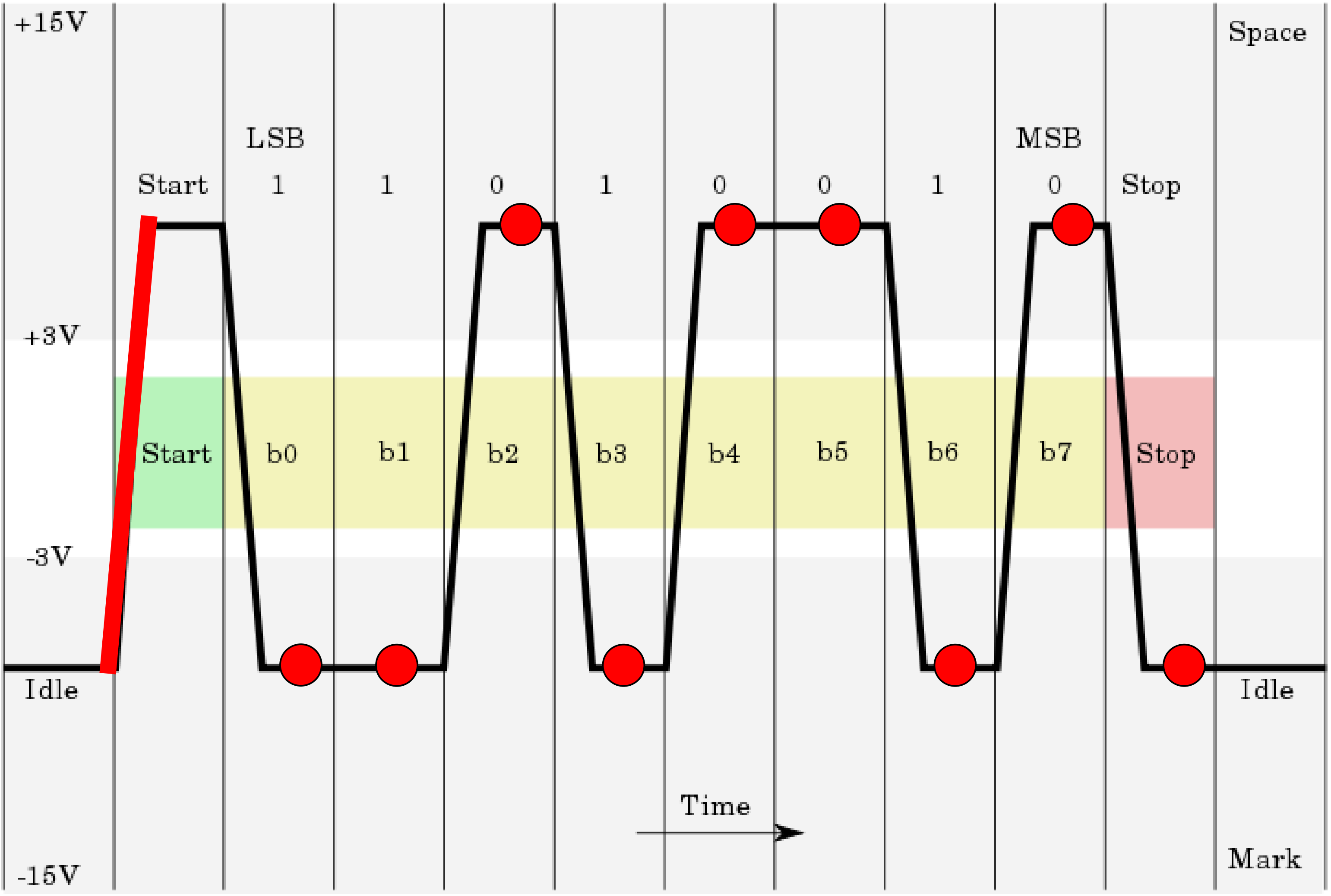
- Signal: **between** RxD/TxD and Ground



RS-232 Modulation



RS-232 Demodulation



RS-232 Delay

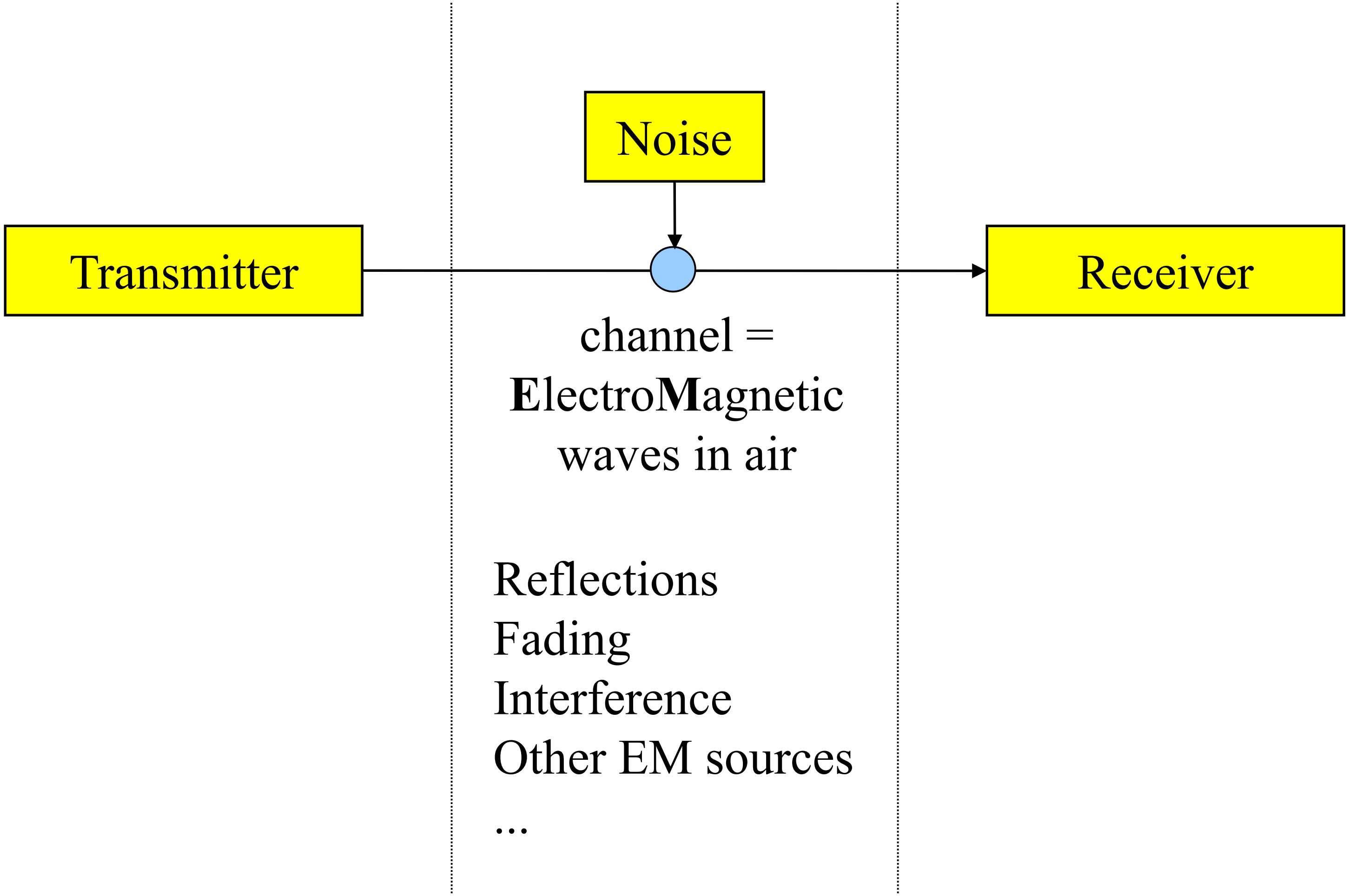
- Packet-based
  - 1 byte (i.e. 8 bits)/ packet
  - 8 data bits + 2 control bits (start/stop) = 10 bits
- Transmission speed
  - max. 115'200 bits/s (bps)
- Propagation speed:
  - approx. c (speed of light)

RS-232 Delay

- Transmission delay
  - 10 bits / 115'200 bps = 86.8 µs
- Signal propagation delay (2 m cable)
  - 2 m / c = 6.6712819 ns
- Processing delay:
  - ~ 1 us (modulation, demodulation, processing)
- Total: ~ 90 µs = 0.09 ms

Wireless Communication

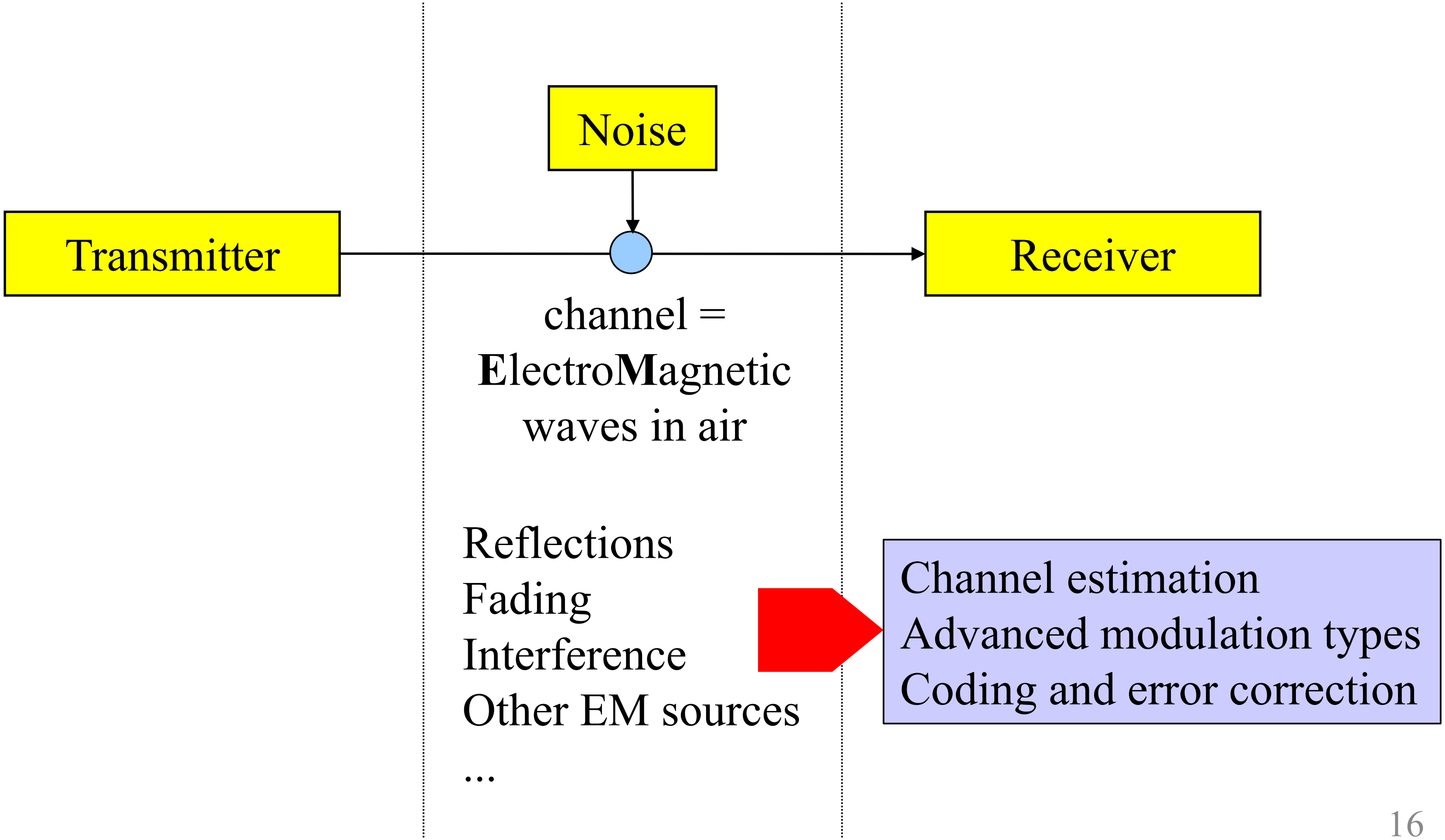
Communication Model



channel =
Electro**M**agnetic
waves in air

Reflections
Fading
Interference
Other EM sources
…

Communication Model



Noise

Transmitter

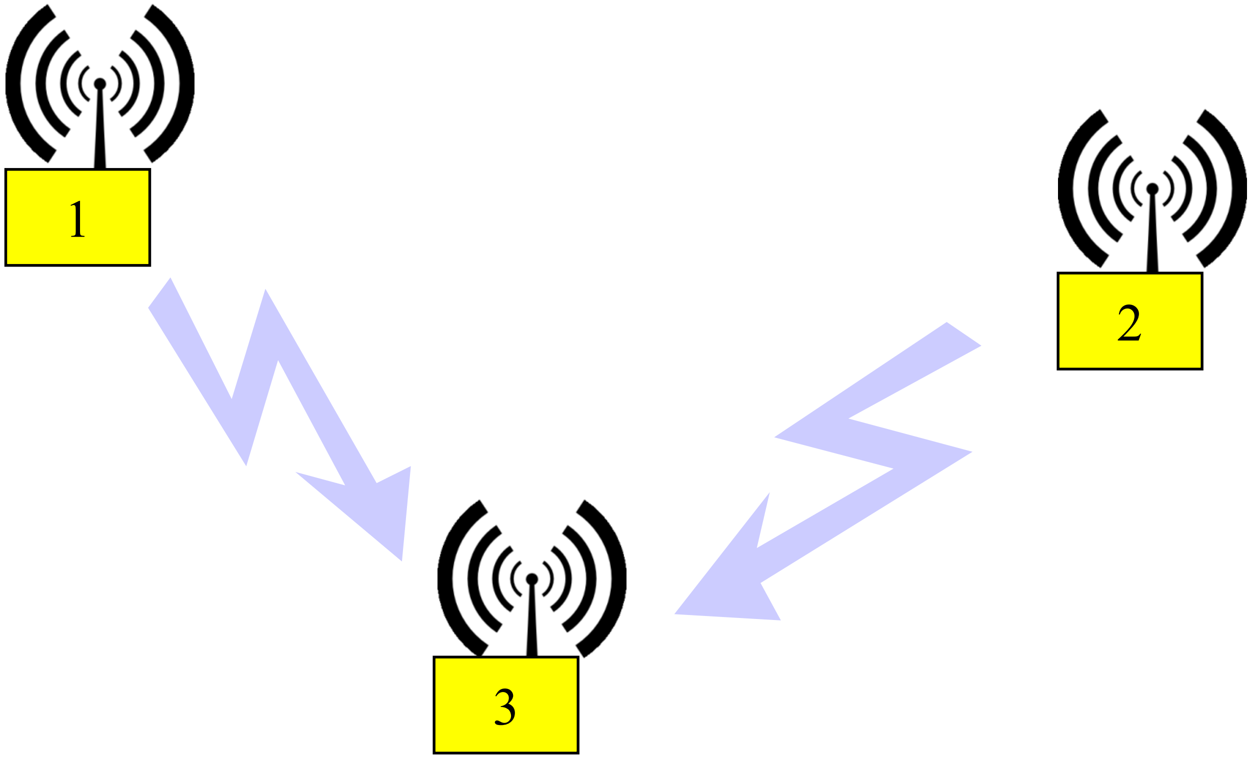
Receiver

channel =
Electro**M**agnetic
waves in air

Reflections
Fading
Interference
Other EM sources
…

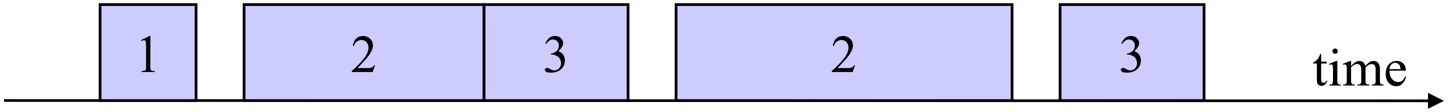
Channel estimation
Advanced modulation types
Coding and error correction

Sharing the Medium



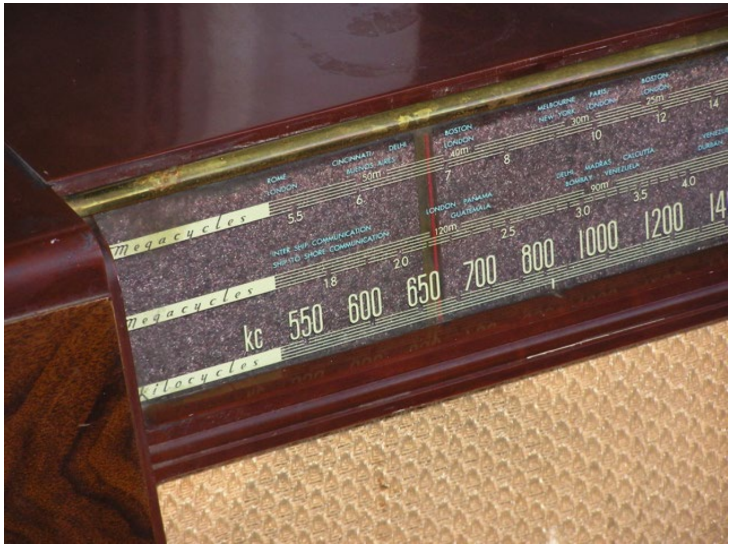
Sharing the Medium

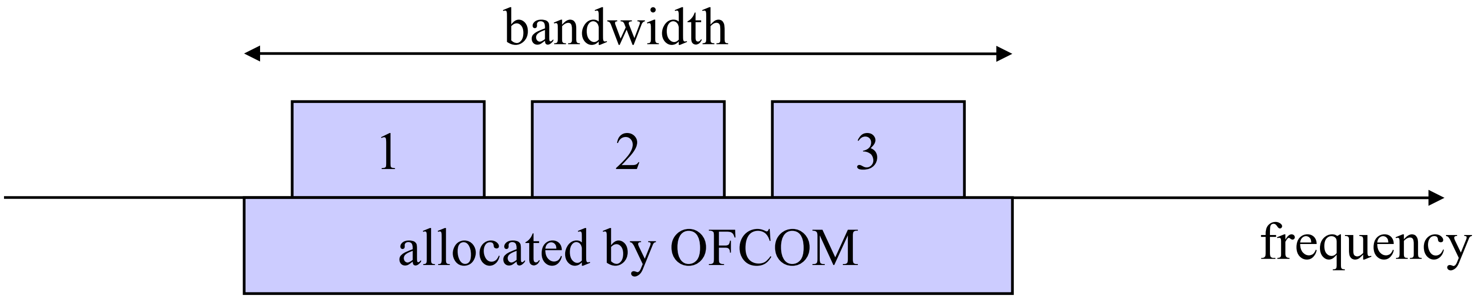
- TDMA
  - – Time-Division Multiple Access
  - – “You shut up while I talk“
  - – Time allocation
    - Fixed, synchronized
      e.g. mobile phones (GSM)
    - Dynamic (check if channel is free)
      e.g. Wireless LAN (802.11b/g/n)



Sharing the Medium

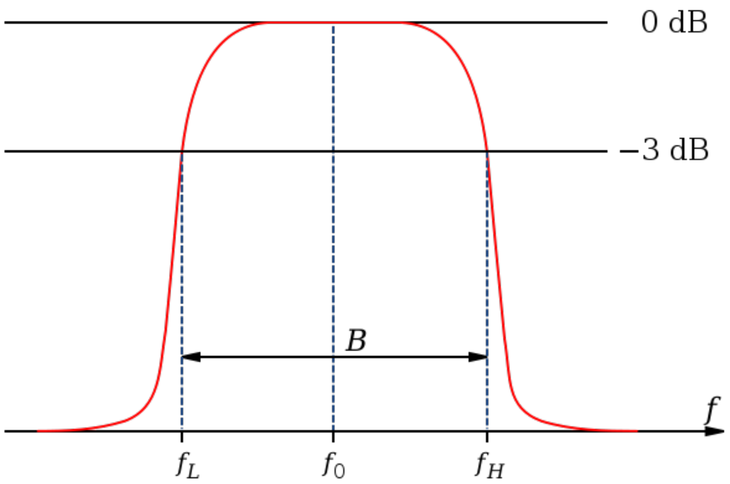
- FDMA
  - – Frequency-Division MA
  - – e.g. FM radio channels
  - – Frequency regulation
    - OFCOM (CH)





Bandwidth

- Can be defined by the OFCOM for multiple channels for a given purpose (in the overall spectrum)
- Can be defined for a single channel as follow:



- B = bandwidth
- f_0 = carrier (channel) frequency
- f_L = low cut-off frequency (typically defined at -3dB)
- f_H = high cut-off frequency (typically defined at -3dB)

-3dB = 50% power (spectral density)
i.e. 10 log(0.5) = -3dB
-3dB = 70% amplitude (spectral amplitude)
i.e. 20 log(0.7) = -3dB

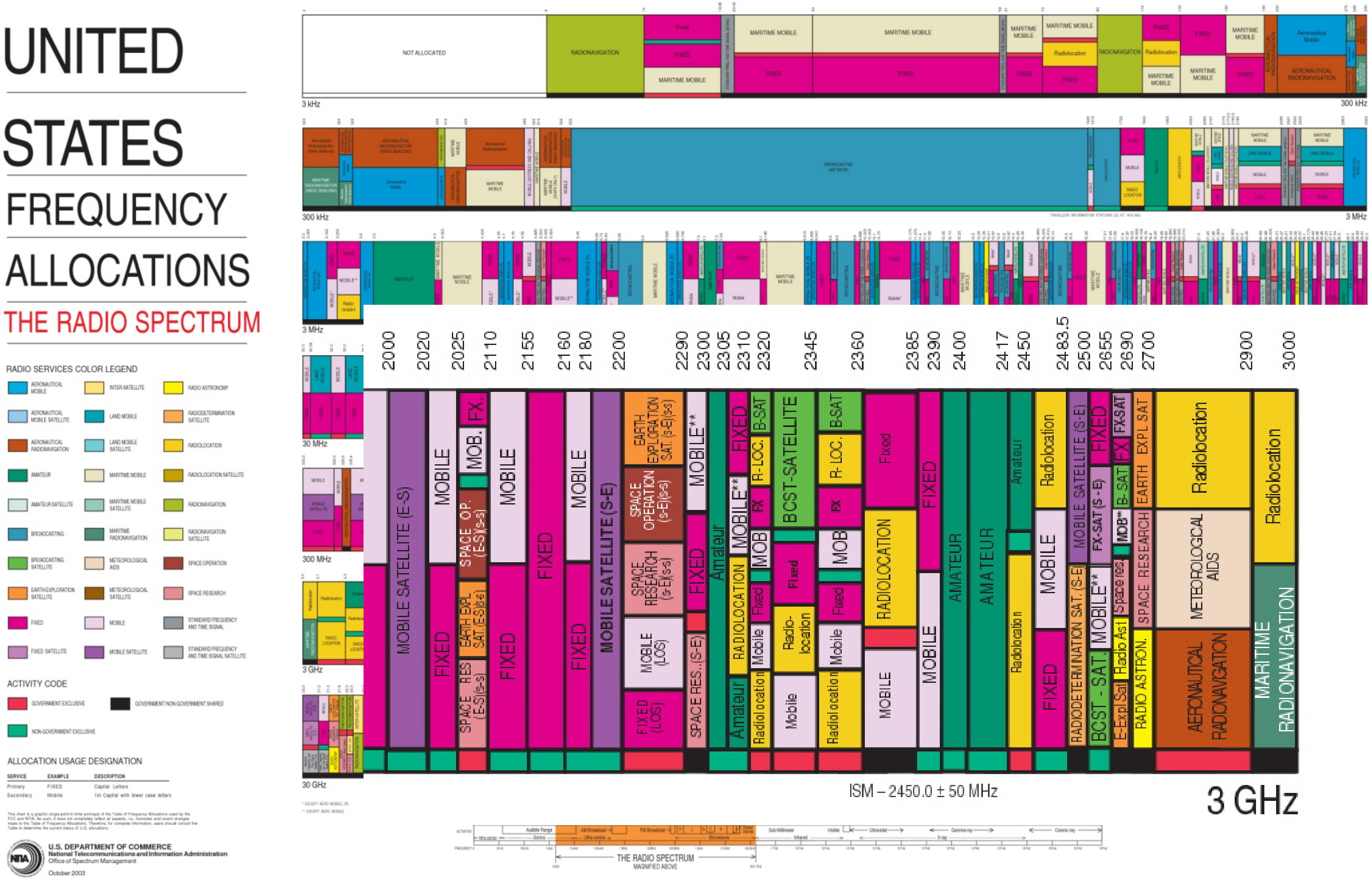
Bandwidth

- FM station broadcasting at 106,4 MHz
  → actually occupies 106,3 MHz – 106,5 MHz
  → Bandwidth = 200 kHz
- Mobile phone (GSM, 2G): 200 kHz (around 900 MHz)
- WLAN/WiFi: 5 MHz (around 2,4 GHz)
- Analog TV station: 6 MHz (around 180 MHz)

What does the bandwidth depend on?

Bandwidth [Hz] ↑ → Data rate (Throughput) [bits/s] ↑

Bandwidth

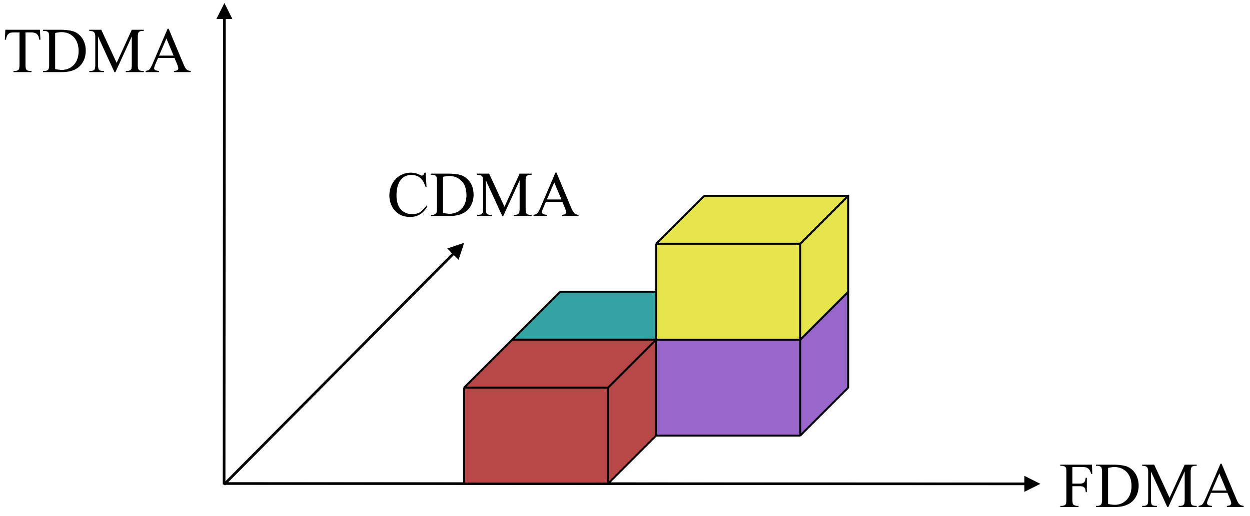

UNITED STATES FREQUENCY ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
2000
2020
2025
2110
2155
2160
2180
2200
2290
2300
2305
2310
2320
2345
2360
2385
2390
2400
2417
2450
2483.5
2500
2655
2690
2700
2900
3000
MOBILE SATELLITE (E-S)
MOBILE
FIXED
SPACE OP. (E-S)(s-s)
SPACE RES. (E-S)(s-s)
EARTH EXPL. SAT. (E-S)(s-s)
MOBILE SATELLITE (S-E)
EARTH EXPLORATION SAT. (s-E)(s-s)
SPACE OPERATION (s-E)(s-s)
SPACE RESEARCH (s-E)(s-s)
MOBILE (LOS)
FIXED (LOS)
SPACE RES..(S-E)
Amateur
RADIOLOCATION
BCST-SATELLITE
B-SAT
R-LOC.
Radiolocation
Fixed
Mobile
AMATEUR
RADIODETERMINATION SAT. (S-E)
MOBILE SATELLITE (S-E)
FX-SAT (S - E)
BCST - SAT.
EARTH EXPL SAT
SPACE RESEARCH
RADIO ASTRON.
METEOROLOGICAL AIDS
AERONAUTICAL RADIONAVIGATION
MARITIME RADIONAVIGATION
ISM – 2450.0 ± 50 MHz
3 GHz
THE RADIO SPECTRUM
MAGNIFIED ABOVE

Sharing the Medium

- CDMA (spread spectrum)
  - Code-Division MA
  - Using different transmission codes
  - e.g. GPS, WiFi, smart phones (3G/4G), Zigbee
  - Interesting properties
    - Wide channels (less fading)
    - Concurrent communication
  - More complex demodulation

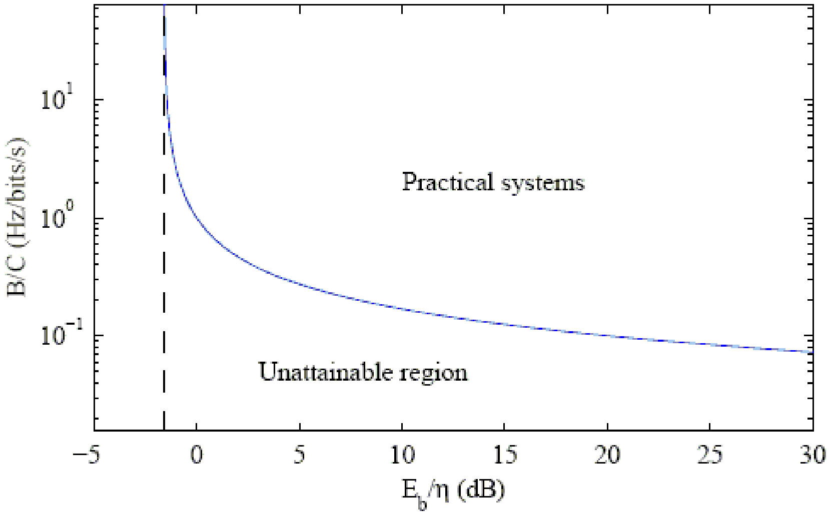
Throughput (bits/s)

- TDMA, FDMA, CDMA can be combined
- Total throughput is shared



Shannon-Hartley Limit

- Hard theoretical limit on throughput
  - More bandwidth = higher throughput
  - More power (SNR) = higher throughput



Bandwidth “dilution”

Bit energy to noise-power spectral density ~ S/N

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

C: capacity (throughput)
B: bandwidth
S: signal power (W)
N: noise power (W)

Power

- Increased power
  - higher throughput
  - higher range
  - mobile systems: shorter battery life
  - increased health risk (?)
- Regulation
  - CH: OFCOM
  - e.g. WLAN: 100 mW

Power

- Unit: W (Watt)
  - Often written in dBm (decibels to 1 mW)

$$P_{dBm} = 10 \log_{10}(P_{mW})$$

- Gain / loss: factors
  - Often written in dB (decibels)

$$F_{dB} = 10 \log_{10}(F)$$

P_{dBm} and Gain/Loss factors

$$P_{dBm} = 10\log\left(\frac{P_W}{1\text{mW}}\right)$$

- 1mW → 10 log(1mW/1mW) → 10 log(1) = 10·0 = 0 dBm
- 2mW → 10 log(2mW/1mW) → 10 log(2) ≈10·0.3 = 3 dBm
- 10mW → 10 log(10mW/1mW) → 10 log(10) = 10·1 = 10 dBm
- 100mW → 10 log(100mW/1mW) → 10 log(100) = 10·2 = 20 dBm

Factors in the chain become sums in a log form:

$$\log(x \cdot y) = \log(x) + \log(y)$$

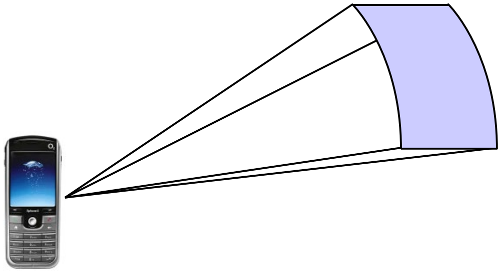
Link Budget

Typical WLAN link budget (100 m, dipole antennas):

TX power	100 mW	20 dBm
TX losses	*0.5	-3 dB
TX antenna gain	*1.6	+2 dB
Free space path loss	$*1.0106*10^{-8}$	-80 dB
RX antenna gain	*1.6	+2 dB
RX losses	*0.5	-3 dB
RX power	0.00000064 mW	*-62 dBm*
RX sensitivity	0.000000003 mW	*-85 dBm*
Margin	200	23 dB

Free Space Path Loss (Friis Law)

- Signal power decay in air:



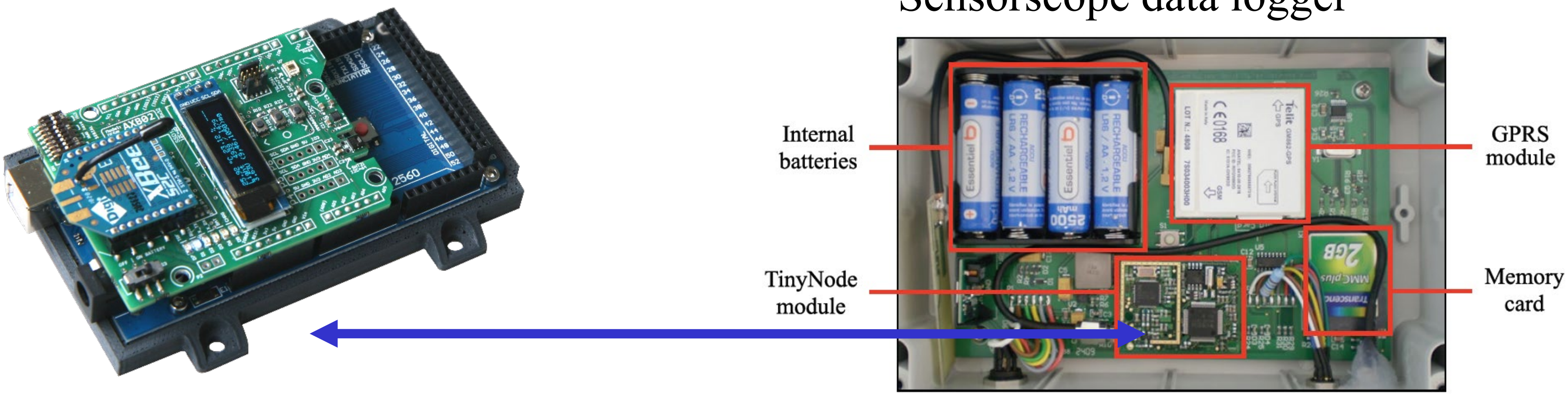
$$L = \left(\frac{4\pi d f}{c} \right)^2$$

$$L_{dB} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.56$$

- Proportional to the square of the distance *d*
- Proportional to the square of the frequency *f*
  - – high frequency = high loss
  - – low frequency = low throughput

Ex.: DISAL Arduino Xbee kit vs. TinyNode

Sensorscope data logger



DISAL Arduino Xbee kit

- Microcontroller:
  - ATMega 2560

- Transceiver:
  - Silicon Labs EM357 (part of the Xbee 802.15.4 module)
  - 2.4 GHz carrier
  - Throughput: up to 250 kbps
  - Range: up to 90 m

TinyNode (Shockfish)

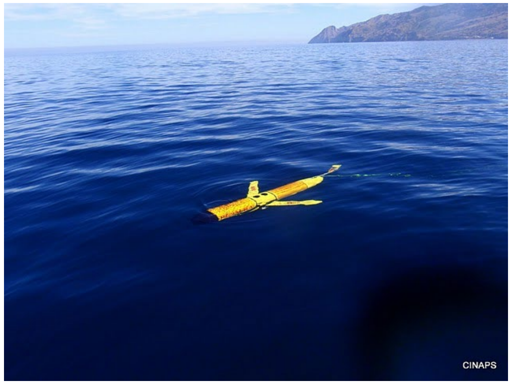
- Microcontroller:
  - TI MSP430

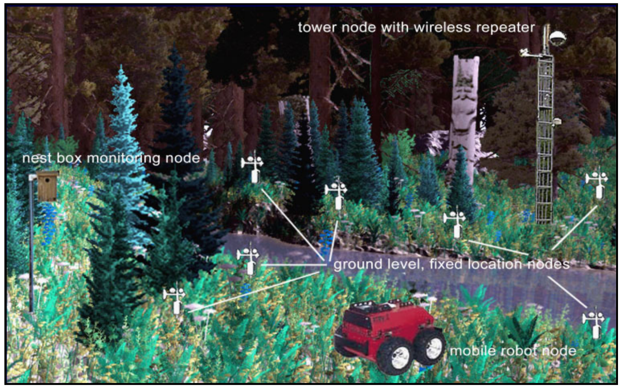
- Transceiver:
  - Semtech XE 1205
  - 868 and 915 MHz carriers
  - Throughput: up to 153 kbps
  - Range: up to 2 km

Mobility in Embedded Systems – Motivation, Autonomy, and Robots

Motivation

- Automation is progressing also in environmental and civil engineering
- Because of the size of the area in which mission must be accomplished (e.g., sensing, monitoring, acting) mobility is key
- Being mobile add complexity and cost at the node level but extend coverage of potentially expensive assets
- Mobile robots become progressively essential tools for automating environmental and civil engineering missions

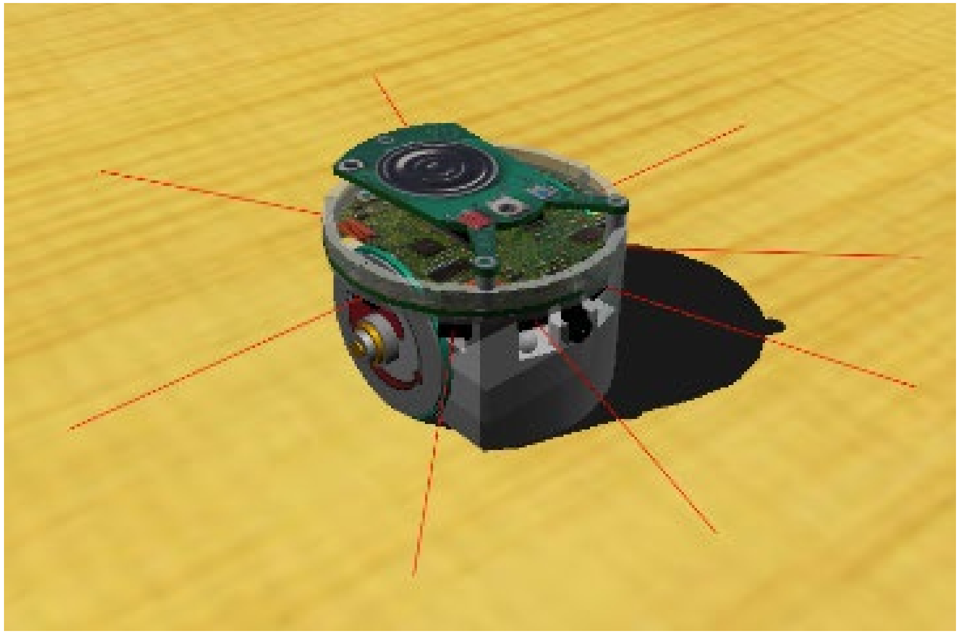




Autonomy

- Different levels/degrees of autonomy
  - Energetic level
  - Sensory, motor, and computational level
  - Decisional level
- Needed degree of autonomy depends on task/environment in which the unit has to operate
- Environmental unpredictability is crucial: robot manipulator vs. mobile robot vs. sensor node

Simulated and Real e-puck



Simulated e-puck (Webots)

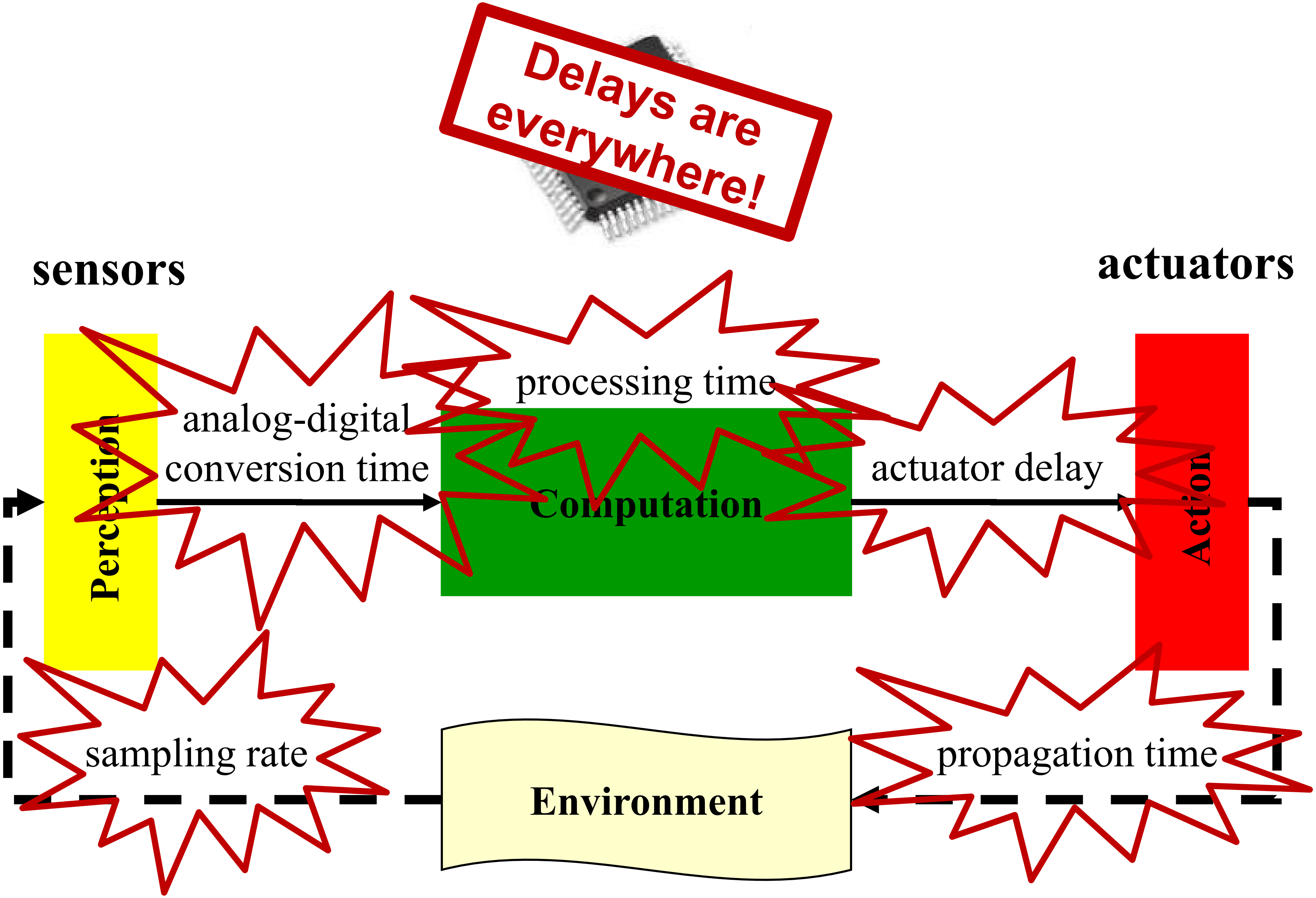
- sensor- and actuator-based
- noise, nonlinearities of S&A reproduced
- kinematic (e.g., speed, position) and dynamic (e.g., mass, forces, friction)

Real e-puck

Simulated and Real e-puck

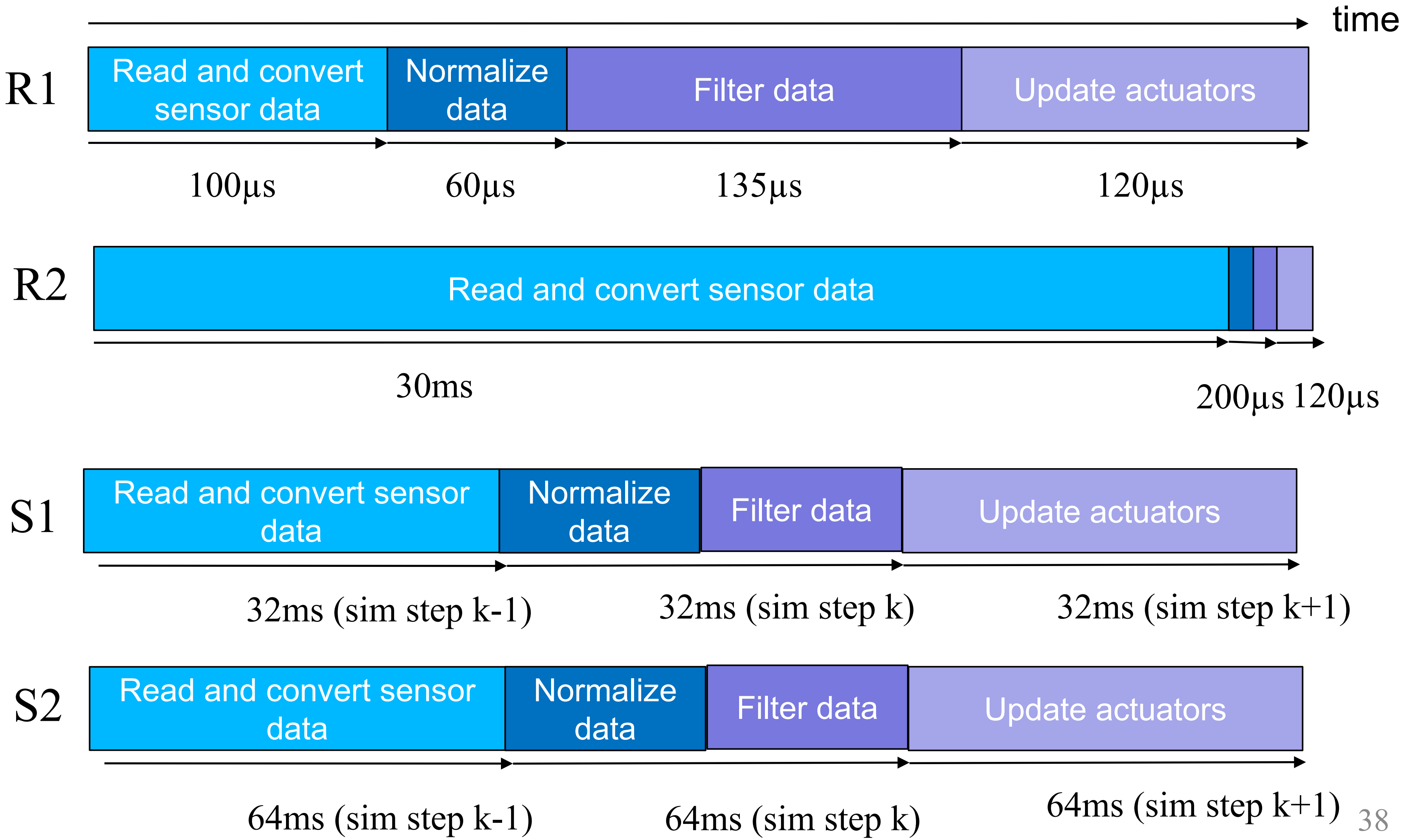
- High-fidelity simulator Webots looks very powerful and realistic but:
  - Manufacturing heterogeneities not reproduced (e.g., all sensor of a certain type are the same, all the robots as well).
  - Noise distributions are typically uniform or Gaussian
  - Sensor field of view simplified (e.g., ray instead of cone)
  - Limitation in computational resources and internal electrical/computational architecture not reproduced
  - World physics approximated (e.g., geometry, communication channel, fluid dynamics) or not reproduced (e.g., chemical dispersion, thermal dissipation, etc.)
  - **Real-time emulation very crudely approximated**
  - …

Example: Real-Time Emulation



Real-time Emulation

R = possible reality situation; S: possible simulation parametrization



time

R1

Read and convert sensor data | Normalize data | Filter data | Update actuators

100µs | 60µs | 135µs | 120µs

R2

Read and convert sensor data

30ms

200µs 120µs

S1

Read and convert sensor data | Normalize data | Filter data | Update actuators

32ms (sim step k-1) | 32ms (sim step k) | 32ms (sim step k+1)

S2

Read and convert sensor data | Normalize data | Filter data | Update actuators

64ms (sim step k-1) | 64ms (sim step k) | 64ms (sim step k+1)

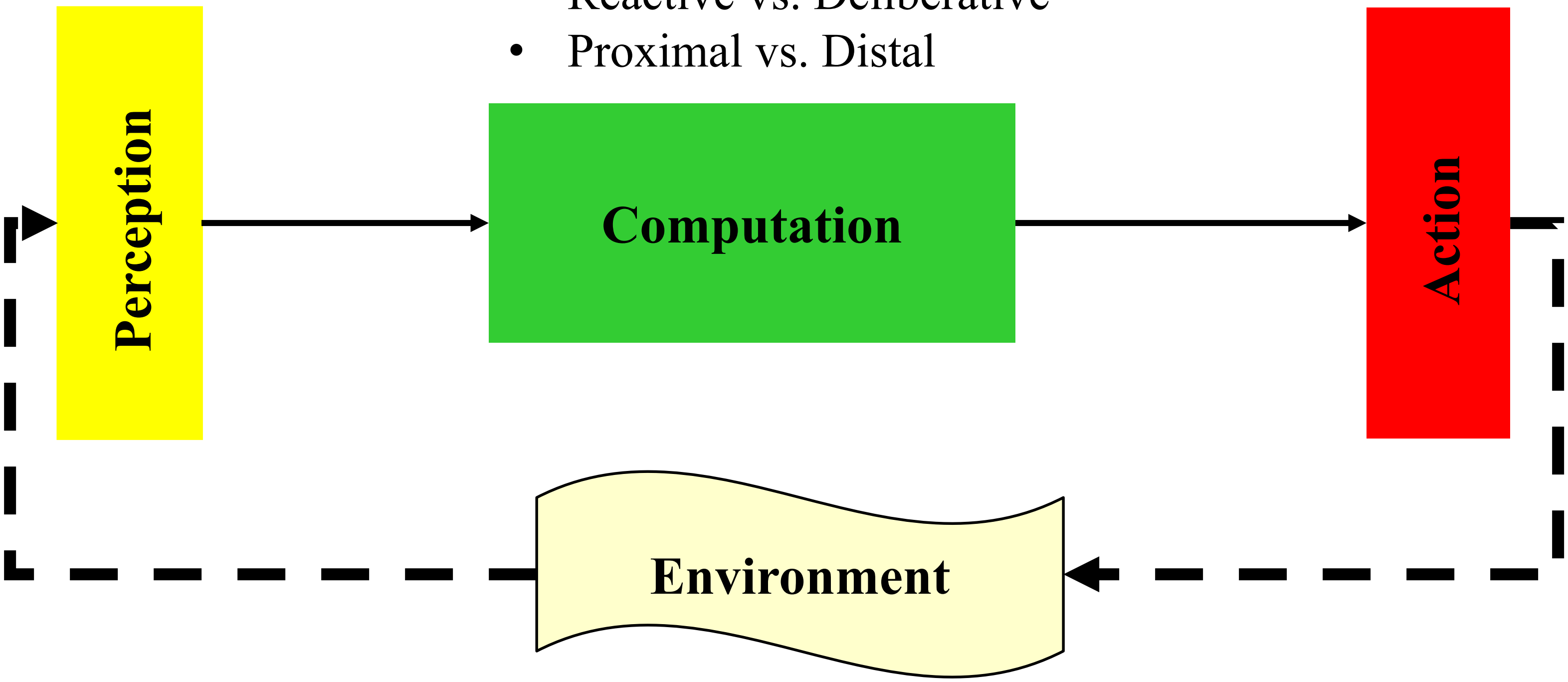
A Simple Taxonomy for Control Architecture in Mobile Robotics

Perception-to-Action Loop for a Mobile Robot

- sensors

- actuators

Controller:
- Reactive vs. Deliberative
- Proximal vs. Distal



Perception

Computation

Action

Environment

Reactive vs. Deliberative Architectures

- Reactive controller:
  - 1 perception-to-action loop horizon
  - No planning, no history stored

- Deliberative controller
  - Multiple perception-to-action loop horizon
  - Planning and history exploitation

- Reactive-deliberative boundary zone:
  - Short history, short look-ahead horizon
  - A few state variables and little memory

Proximal vs. Distal Architectures

- Proximal:
  - close to sensor and actuators; no control hierarchy or layering
  - high flexibility in shaping the behavior by changing parameters and keeping the structure fixed
  - light architecture, fast execution time
  - works well when few resources available
  - difficult to engineer in a “human-guided” way

Proximal vs. Distal Architectures

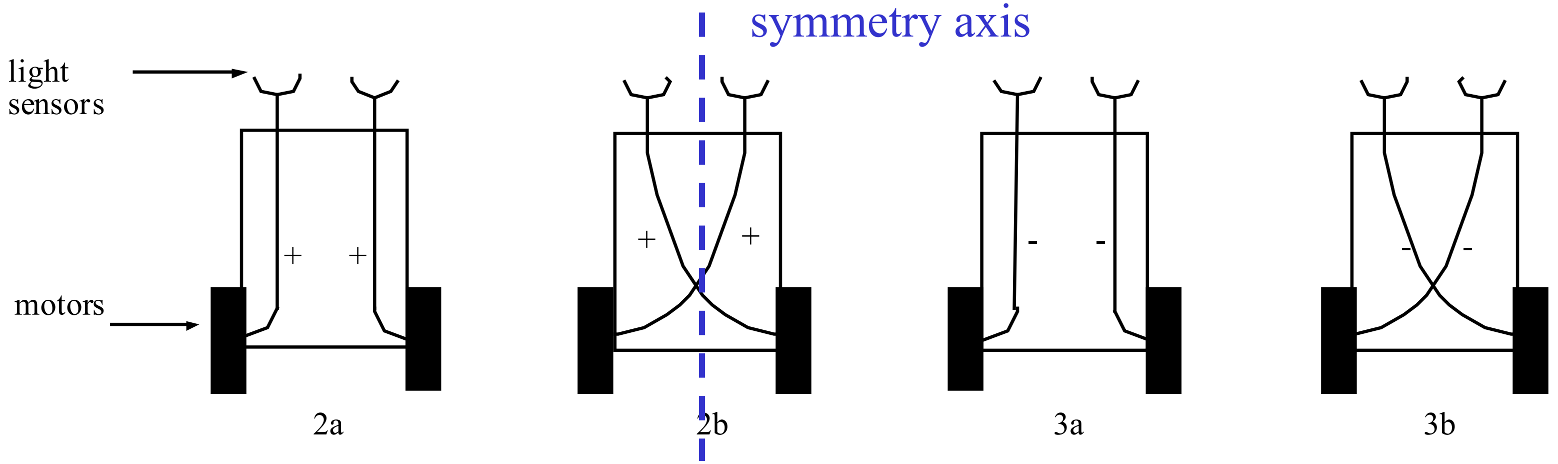
- Distal:
  - farther from sensor and actuators; some control hierarchy or layering possible
  - less flexibility in shaping the behavior (behavioral module or basic behavior definition; flexibility only in the module "wiring" typically)
  - not always computationally light architecture
  - easier to engineer in a "human-guided" way because of the existence of modules (often hand coded)

Selected Reactive Architectures for Mobile Robots and their Application to Obstacle Avoidance

Overview

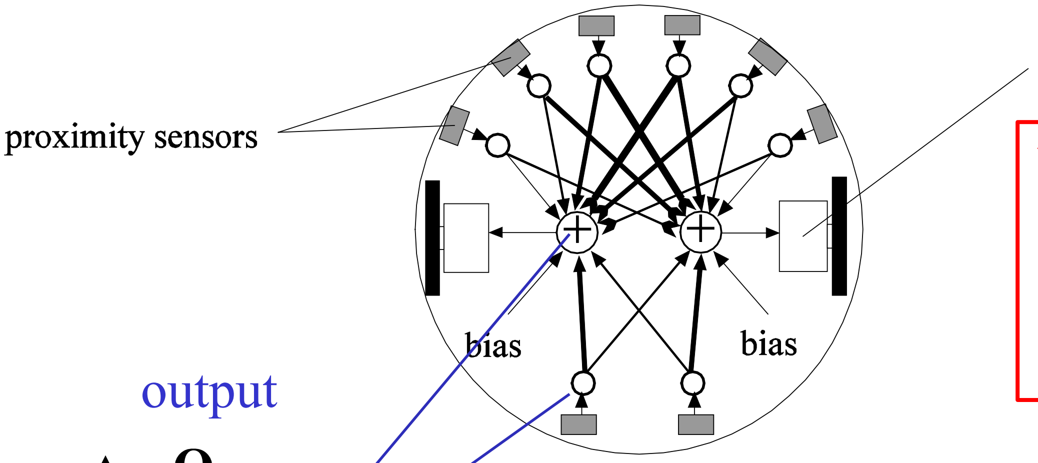
- Five “classical” examples of reactive control architecture for solving the same problem: obstacle avoidance.
- Two proximal: Braitenberg and Artificial Neural Network
- Three distal: Rule-based, Subsumption and Motor Schema, both behavior-based

Ex. 1: Braitenberg's Vehicles

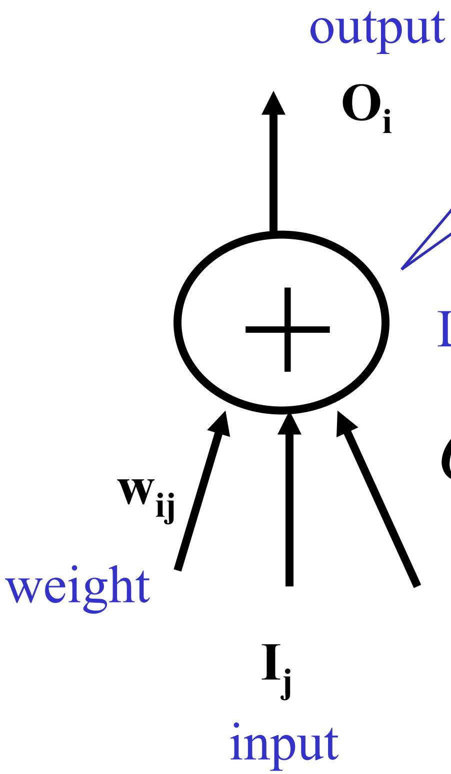


- Work on the difference (gradient) between sensors
- Originally omni-directional sensors; works also with directional sensors (sharper, potentially discontinuous differences at the sensory level -> more jerky movement)
- Originally: light sensors
- \+ excitation, - inibition; linear controller (out = signed coefficient * in)
- Symmetry axis along main axis of the vehicle (----)
- See also lecture Week 7 and Lab 6

Ex. 1: Braitenberg's Vehicles



With proximity sensors:
- m = 8
- local sensors -> must add a bias otherwise no stimulus



inhibitory conn. (negative weight)

excitatory conn. (positive weight)

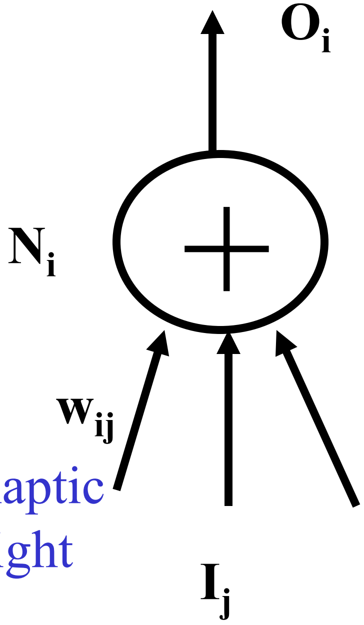
Linear summing & normalizing operator

$$O_i = Kf(x_i) = Kx_i$$

K: normalization constant

$$x_i = \sum_{j=1}^{m} w_{ij} I_j + I_0$$

Ex. 2: Artificial Neural Network



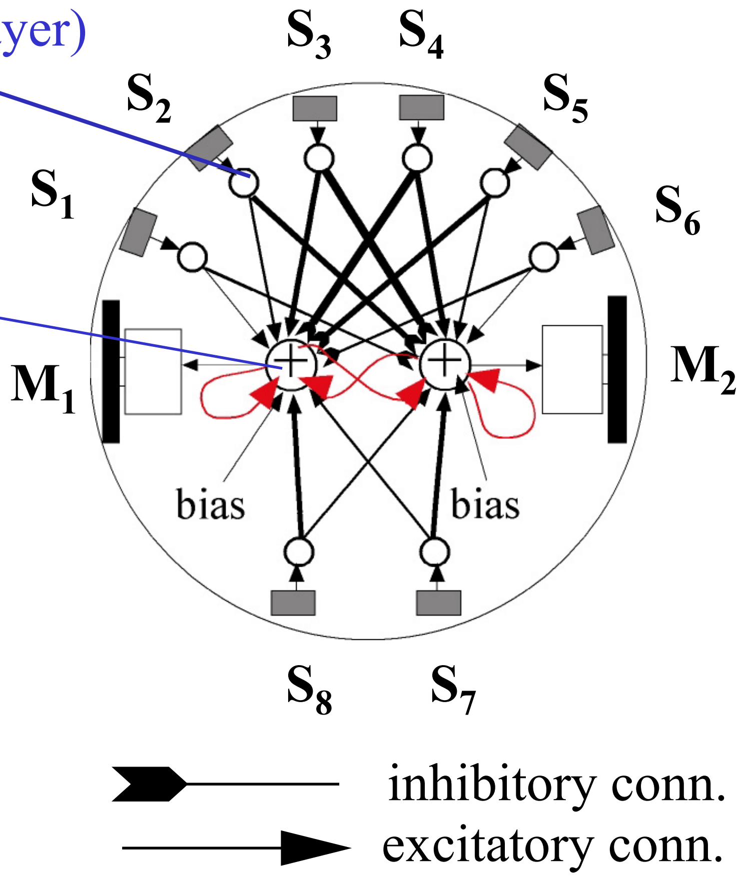
output

synaptic weight

input

neuron (output layer) with sigmoid transfer function f(x)

neuron (input layer)



inhibitory conn.

excitatory conn.

$$O_i = Kf(x_i)$$

$$f(x) = \frac{2}{1+\mathrm{e}^{-x}} - 1$$

$$x_i = \sum_{j=1}^{m} w_{ij} I_j + I_0$$

K: normalization constant

Ex. 3: Rule-Based

Rule 1:
if (proximity sensors on the left active) **then**
  turn right

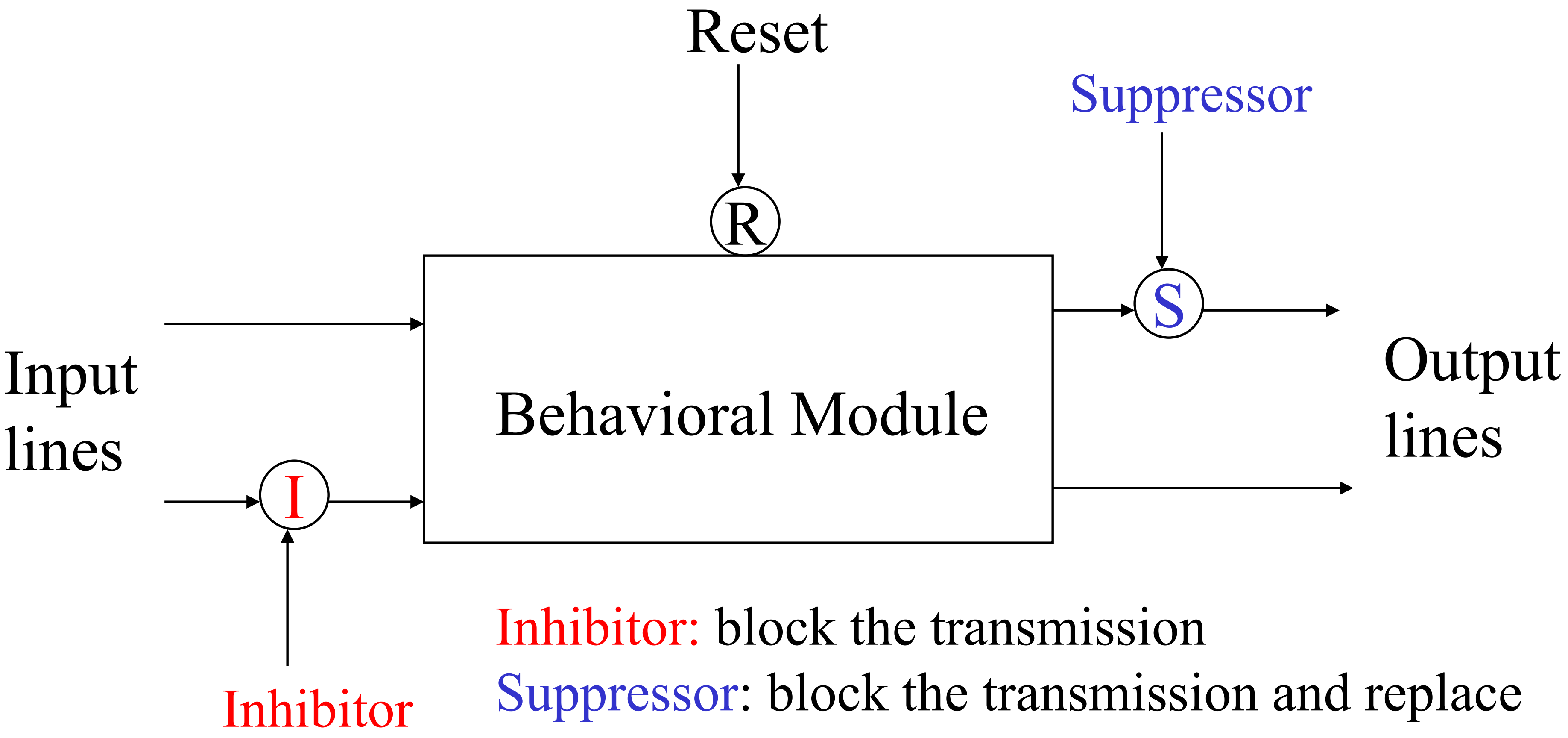
Rule 2:
if (proximity sensors on the right active) **then**
  turn left

Rule 3:
if (no proximity sensors active) **then**
  move forwards

Subsumption Architecture

- Rodney Brooks (1986)
- Precursors: Braitenberg (1984), Walter (1953)
- Behavioral modules (basic behaviors) represented by Augmented Finite State Machines
- Response encoding: predominantly discrete (rule based)
- Behavioral coordination method: competitive (priority-based arbitration via inhibition and suppression)

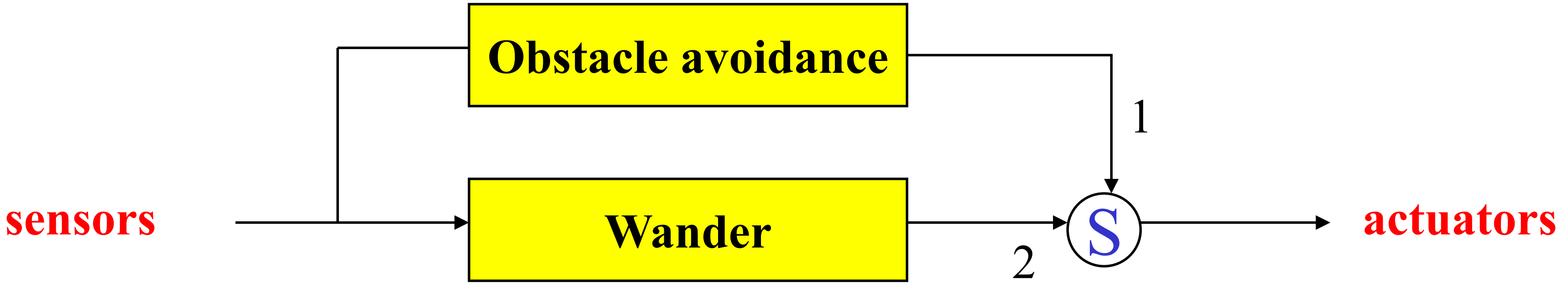
Augmented Finite State Machine



Inhibitor: block the transmission

Suppressor: block the transmission and replace the signal with the suppressing message

Ex. 4: Behavior-Based with Subsumption



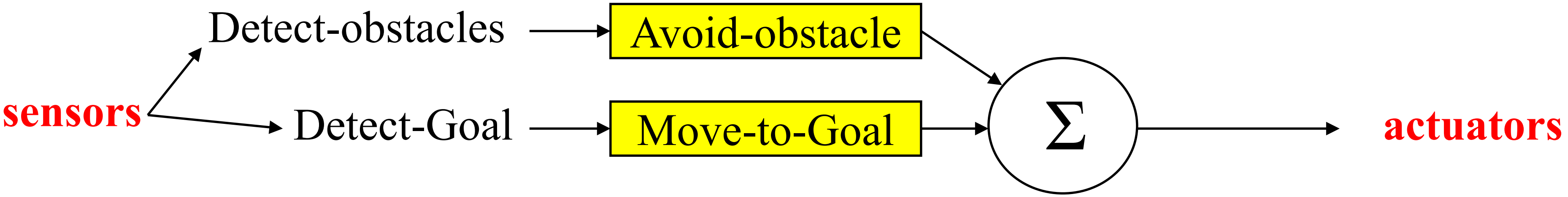
(1 suppresses and replaces 2)

Concrete implementation within basic behaviors:
Obstacle avoidance: Braitenberg without bias, rule-based, etc.
Wander: bias on motors (straightforward motion), random walk, etc.

Motor Schemas

- Ronald Arkin 1987, Georgia Tech
- Precursors: Arbib (1981), Khatib (1985)
- Parametrized behavioral libraries (schemas)
- Response encoding: continuous using potential field analog
- Behavioral coordination method: cooperative via vector summation and normalization

Ex. 5: Behavior-Based with Motor Schemas



Note: each motor schema generate an output vector that then gets summed up and normalized for controlling the actuators

Visualization of Vector Field for Ex. 5

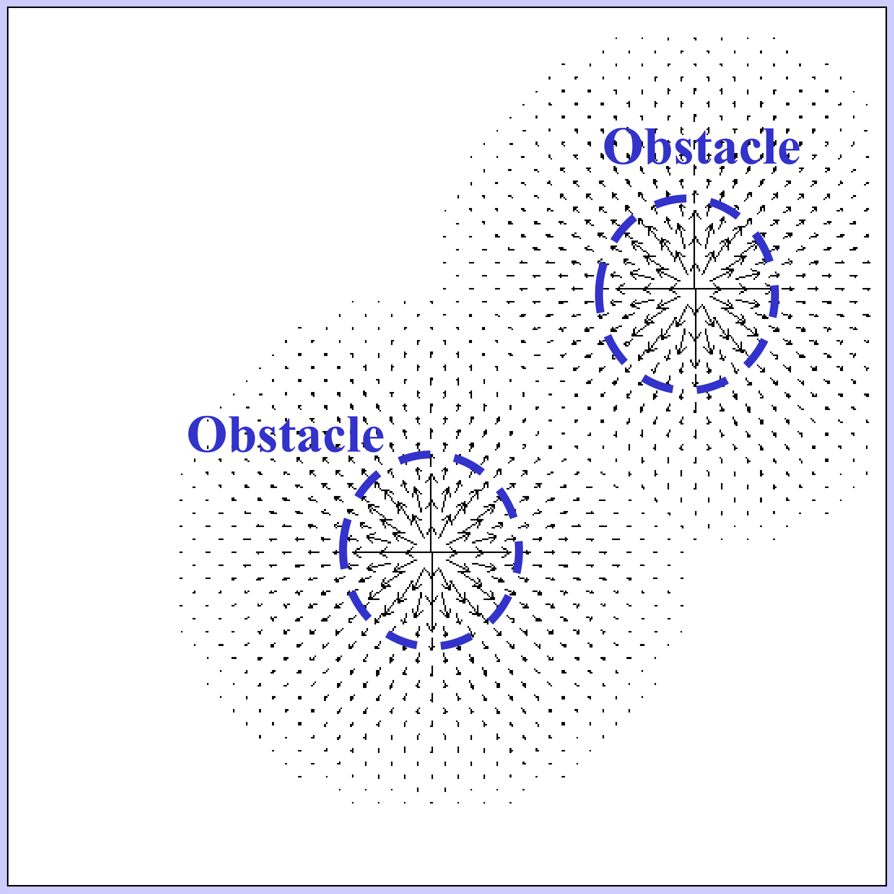
Avoid-obstacle

Vector = [magnitude, direction]

$$V_{\text{magnitude}} = \begin{cases} 0 & \text{for} \quad d > S \\ \dfrac{S-d}{S-R}G & \text{for} \quad R < d \le S \\ \infty & \text{for} \quad d \le R \end{cases}$$

S = obstacle's sphere of influence
R = radius of the obstacle
G = gain
D = distance robot to obstacle's center

$V_{\text{direction}}$ = radially along a line between robot and obst. center, directed away from the obstacle



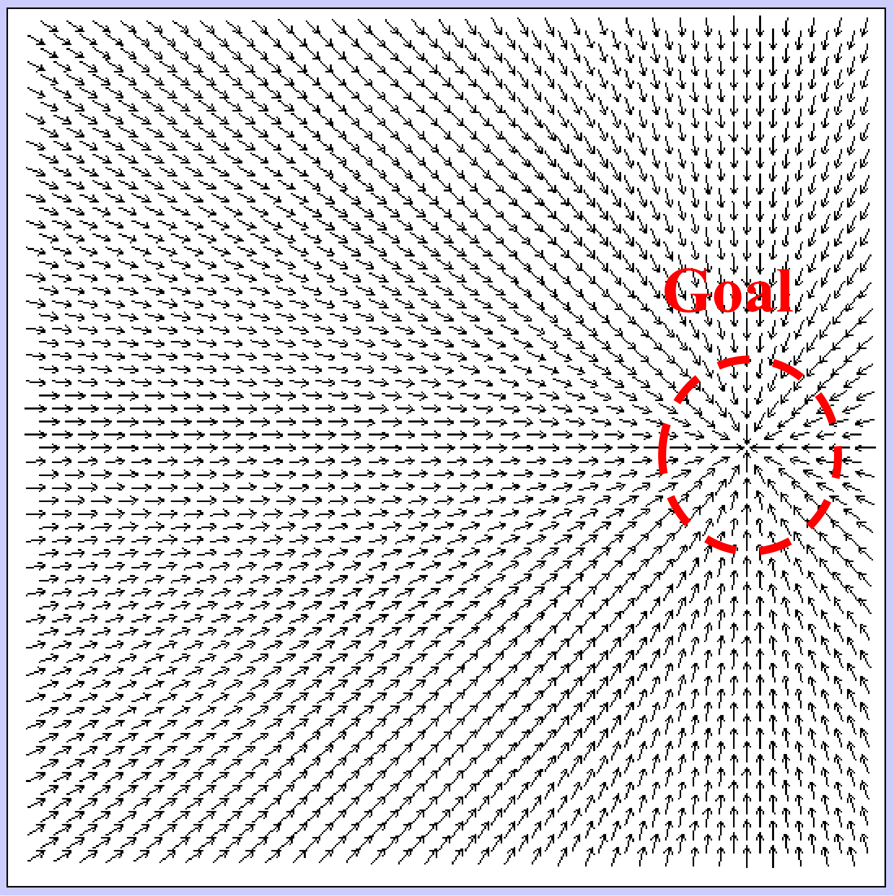
Visualization of Vector Field for Ex. 5

Move-to-goal

Vector = [magnitude, direction]

$V_{magnitude}$ = fixed gain value

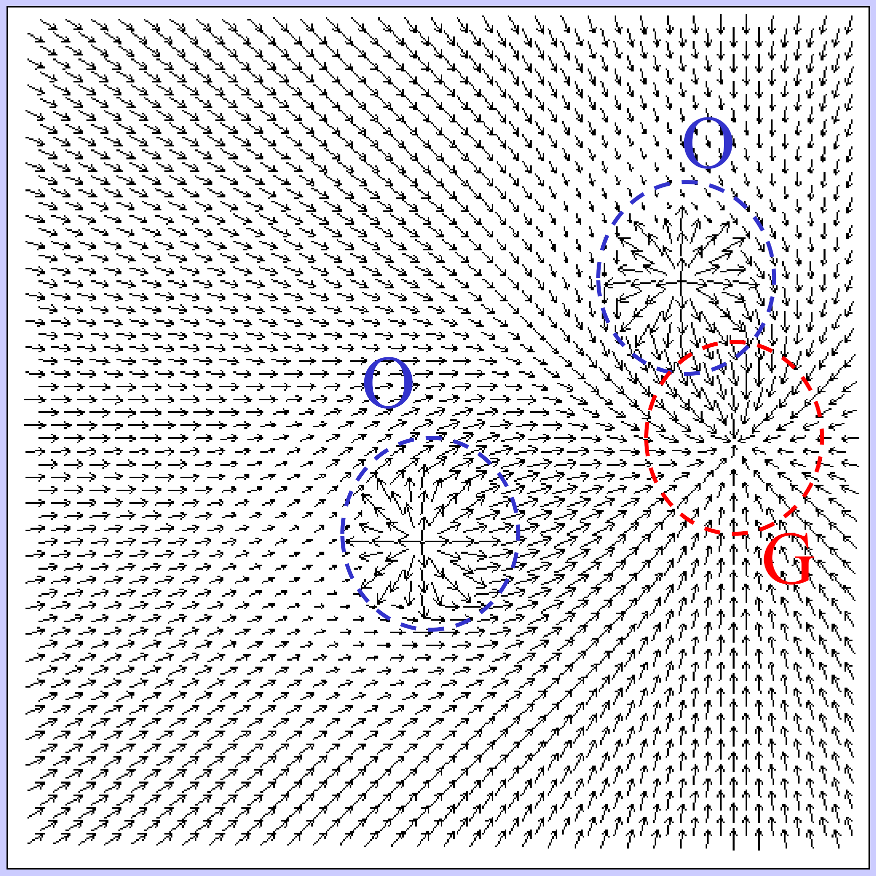
$V_{direction}$ = towards perceived goal



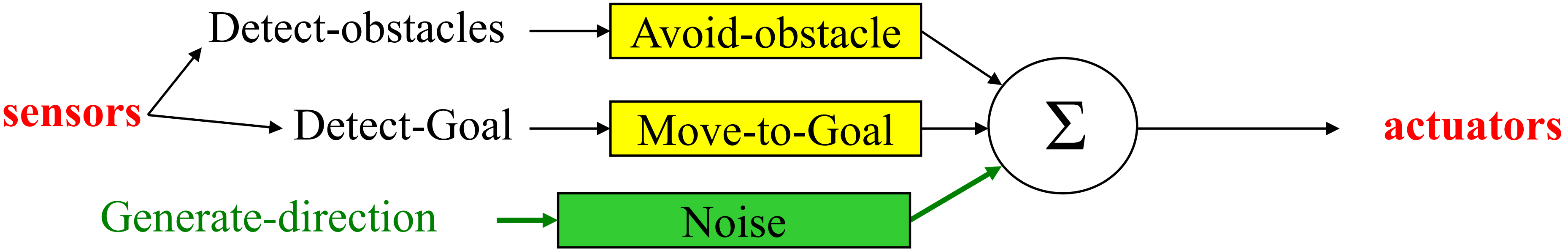
Visualization of Vector field for Ex. 5

Avoid-obstacle + **move-to-goal**

Linear superposition
(vectorial weighted sum)



Ex. 5: Issue with Motor Schemas



To avoid getting stuck in local minima of the vector field (typical problem of vector field approaches)

Alternative more complex approach: use harmonic potential functions (explicitly designed for not generating local minima)

Conclusion

Take Home Messages

- Communication plays a key role in embedded systems in general and in mobile robots in particular
- Some key concepts in communication systems
  - Bandwidth, real throughput, TDMA, FDMA, CDMA …
  - Transmitted/received power and corresponding losses
- The complexity of a controller depends on the degree of autonomy, mission to accomplish, and environmental conditions
- Controllers are characterized by parameters and a structure (architecture)
- A given overall behavior of the device can be obtained with different control architectures
- Controllers can be classified along two main axes: proximal vs. distal, reactive vs. deliberative

Additional Literature – Week 8

Pointers

- e-puck website: http://www.e-puck.org/

Articles

- Brooks R., “A robust layered control system for a mobile robot”, *IEEE J. of Robotics and Automation*, 2(1): 14 – 23.

Books

- Braitenberg V., “Vehicles: Experiments in Synthetic Psychology”, MIT Press, 1986.
- Siegwart R., Nourbakhsh I. R., and Scaramuzza D., “Introduction to Autonomous Mobile Robots”, 2nd edition, MIT Press, 2011.
- Arkin R. C., “Behavior-Based Robotics”. MIT Press, 1998.
- Everett, H. R., “Sensors for Mobile Robots, Theory and Application”, A. K. Peters, Ltd., 1995