ENERGY CONSUMPTION

- **Duty cycle:** $\boxed{\frac{\text{active time}}{\text{total period}}} = x \in [0,1]$ if $(x == 0 \| x == 1)$
  $\Rightarrow$ Continual signals

- **Energy** and **power** are measured in **joule** and **watts**:

$$\boxed{1J = 1W \cdot sec}$$

- in electromagnetism $1W$ = the work performed when a current of 1A flows to an electrical potential difference of 1V

$$\boxed{1W = 1V \cdot 1A}$$

- In direct current the voltage is constant
  $\Rightarrow$ power and energy only depend on the current (Ampere)

$\Rightarrow$ Hence can express both ENERGY STORED and ENERGY CONSUMED in $\boxed{mAh}$

$$\Rightarrow \boxed{mAh \cdot V = J}$$

- **MICROPROCESSOR energy cost:** E_μ (per cycle)

$$E_\mu = C_\mu^{full} \cdot dc_\mu + C_\mu^{idle} \cdot (1 - dc_\mu)$$

- C_μ^{full} = full energy cost microprocessor
- C_μ^{idle} = idle energy cost microprocessor
- dc_μ = % duty cycle microprocessor

- **RADIO energy cost:** E_ρ (per cycle)

$$E_\rho = C_\rho^T \cdot dc_\rho^T + C_\rho^R \cdot dc_\rho^R + C_\rho^{idle} \cdot (1 - dc_\rho^T - dc_\rho^R)$$

- C_ρ^T = radio Transmission energy cost
- C_ρ^R = radio Receival energy cost
- C_ρ^{idle} = radio idle energy cost
- dc_ρ^T / dc_ρ^R = % of transmitting/receiving Duty cycle

- LOGGER / SENSOR BOARD cost: (same stuff) $\Rightarrow$ TOTAL ENERGY COST PER DUTY CYCLE: $E = E_\mu + E_\rho + E_\lambda + E_\sigma$
  (E_λ = logger, E_σ = sensor board)

- **LIFETIME** (in number of duty cycle):

$$\text{lifetime} = \frac{B_0 - L}{E}$$

- B_0: initial battery charge (during lifetime)
- L: battery charge lost (during lifetime) due to battery leaks
  → (depends on the lifetime
- based on the charge loss/cycle $\mathcal{E}$

- **BATTERY CHARGE AT CYCLE n**

$$B_n = B_{n-1} \cdot (1 - \mathcal{E}) - E$$

$$\Rightarrow B_n = B_0 \cdot (1 - \mathcal{E}) + \frac{E((1-\mathcal{E})^n - 1)}{\mathcal{E}}$$

- device lifetime is given by $n : B_n = 0$
  (in practice the device stops working before than that)

Consider this program and the table of energy consumption in the different states. Compute:

- the energy consumption of the device per single hour
- the expected lifetime of the device

```
                  ...
                  void loop() {
                   turnOn(analogSensor);
4 milliseconds     int sensorValue = analogRead(A0);
                   turnOff(analogSensor);

1 milliseconds     float voltage = sensorValue*
                           (5.0 / 1023.0);

                   turnOn(radioInterface);
15 milliseconds    Serial.println(voltage);
                   turnOff(radioInterface);

380 milliseconds   idle(380);
                  }
```

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	1	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity	2000	mAh

Ampere

Kiloampere (kA) = 10^{-3}
Ampere (A) = 1
Milliampere (mA) = 1'000
Microampere (µA) = 1'000'000

- Energy consumption per hour:

1) PROCESSOR DC = $\frac{\cancel{20}\,1}{\cancel{400}\,20} = \frac{1}{20}$ ←%
2) RADIO DC = $\frac{\cancel{15}\,3}{\cancel{400}\,80} = \frac{3}{80}$
3) SENSOR DC = $\frac{\cancel{4}\,1}{\cancel{400}\,100} = \frac{1}{100}$

processor:
$$E_p : C_p^{full} \cdot dc_p + C_p^{idle} \cdot (1 - dc_p) =$$

radio:
$$E_p = C_p^{T} \cdot dc_p^{T} + C_p^{R} \cdot dc_p^{R} + C_p^{idle} \cdot (1 - dc_p^{R} - dc_p^{T})$$

sensor
$$E_\sigma = C_\sigma^{full} \cdot dc_\sigma + C_\sigma^{idle} \cdot (1 - dc_\sigma)$$

- energy consumption in 1 hour: 21,08 J
- lifetime of the device

	Active	Idle
Processor	$8\,mA \cdot \frac{1}{20} = 8'000'000\,\mu A \cdot \frac{1}{20} = 400'000\,\mu A$	$15\,\mu A \cdot \frac{19}{20} = 14,25\,\mu A$
Radio	$1\,mA \cdot \frac{3}{80} = 1'000'000\,\mu A \cdot \frac{3}{80} = 37'500\,\mu A$	$20\,\mu A \cdot \frac{77}{80} = 19,25\,\mu A$
Sensor	$5\,mA \cdot \frac{1}{100} = 5'000'000\,\mu A \cdot \frac{1}{100} = 50'000\,\mu A$	$5\,\mu A \cdot \frac{99}{100} = 4,95\,\mu A$
Total	$487'500\,\mu A = 0,4875\,mA$	$38,45\,\mu A = 3,825 \cdot 10^{-5}$

$= 4,88 \cdot 10^{-4}\,A$ $\qquad = 3,85 \cdot 10^{-8}\,A$

$E = A^{all} + I^{all} = 0,0004880\,A$

$W = A \cdot V = 0,0004880\,A \cdot 12\,V = 0,005856\,W$

$1\,J = 1\,W \cdot 1\,sec \Rightarrow$

$\Rightarrow J = 0,005856 \cdot 3'600 = 21,08\,J$

0,038 mAh   1,205 mAh

lifetime 2000 mAh / 1,243 mAh ← power consumption in 1 hour

- sample at 20 Hz
  - sensor + micro 0,5 ms
  - in 2 sec 40 samples
  - wait rate to DC

void loop ≤ 5
0,5 ms { sample (x)
y[i] = x }
0,2 ms transmit(y)
4,3 idle (4,3 ms)

• Sensor: 0,5 ms = $\frac{0,5\ ms}{5\ ms}$ = 0,1 ms
• Processor: 0,5 ms + 2 ms = 2,5 ms = $\frac{2,5\ ms}{5\ ms}$ = 0,5 ms
• Radio: 2 ms = $\frac{2\ ms}{\cancel{5\ ms}}$ = 0,4 ms =

$\frac{20\ hz}{5\ ms} = 4$

sensor + processor + radio
0,02
0,5 · 0,02

2,5 ms

1 Hz = 1 ciclo al secondo
20 Hz = 20 cicli al secondo

20 : 1000 ms = x : 2 ms
$x = \frac{20 \cdot 2}{1000} / 5 =$
aspetto 5 sample
= 0,08

20 letture : 1 second
20 letture : 1.000 ms = x : 0,5 ms
$x = \frac{20 \cdot 0,5}{1000} = 0,01$

$\frac{1}{20} = 0,5$

• sampling at 20 Hz (0,5 ms (proc + sensor)
  • Hr every 2 s (based on 40 sample)
  • Send packet 2 ms

DC of sampling: DC processor + sensor = 0,5 ms (sampling time) / 0,05 sec
sampling Period = 0,01

⇒ $\frac{0,05}{0,5}$

DC trans: DC radio + proc = 2 ms (Trans time) / 0,25 sec (trans. period) = 0,008
over period: 250

power comp of sens 1hr: 5 mAh · 0,01 + 5 µAh * 0,99 = 0,055 mAh

processor 1h: 0,018 * 8 mAh + 0,982 * 15 µAh = 0,1587 mAh

Radio 1h: 0,008 * 20 mAh + 0,992 · 20 µAh = 0,1798 mAh

TOTAL: 0,3935 mAh   Lifetime $\frac{2000\ mAh}{0,3935\ mAh}$ = 5082 h es 2

- Sampling requires: 0,5 ms (processor + sensor) $\Rightarrow$ 20 : 1000 mS = x : 0,5 mS

20 hz

$x = \frac{20 \cdot 0,5}{1000} = 0,01$

- Computing HR (processor) = every 2 sec: 5 ms

2 sec

20 : 1000 mS = x : 5 mS

$x = \frac{20 \cdot 5}{1000} = \boxed{0,1}$ / 40 samples: 0,0025

SOL.:

1 thread (50 ms) DC sample: 0,5 ms (sampling) / 0,05 sec ( ) = 0,01 V

2 nd (2 sec) DC proc: 5 ms / 2 s = ,0025 V

3 rd (10 sec) DC trans: 2 ms (transtime) / 10 sec (transm period) =

= 0,0002

Power cons sensor 1h: 5 mAh · 0,01 + 5 µAh · 0,99 = 0,055 mAh

processor: 8 mAh · 0,0127 + 15 µAh · 0,9873 = 0,1164 mAh

radio: 0,0002 · 20 mAh + 0,1998 · 20 µAh = 0,024 mAh

TOTAL in 1h = 0,1954 mAh

LT = 2000 mAh / 0,1916 mAh = 10,235 h

Exercise 1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photo-diode on the wrist at 20 Hz
  - sampling the sensor takes 0.5 ms
  - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
- Transmit (from time to time… see below) a data packet to the server:
  - The average time required to transit is 2 ms
  - Requires both processor and radio active

Compute the energy consumption and the lifetime of the device if it sends all the samples to a server:

- Stores 5 consecutive samples from the photodiode
- Transmits the stored 5 samples to the server
- The server computes HR (hence the device **does not compute HR**)

Disregard battery leaks.

Millisec ms | NANOS ns | SEC s | MICROS µs | MIN m | ORE h

• Transmits the stored 5 samples to the server

Duty cycle of sampling: Duty cycle of transmitting:

DC of processor + sensors: 0.5 milliseconds (sampling time) / 0.05 seconds (sampling period)= 0.01

DC of radio + processor: 2 milliseconds (transmit time) / 0,25 seconds

- 20 Hz => sampling period: $\frac{1}{20} = 0{,}05$ secondi
- DC (processing + sensor) = $\frac{\text{sampling time}}{\text{Sampling period}} = \frac{0{,}5 \text{ ms}}{0{,}05 \text{ sec}} = \frac{0{,}0005 \text{ s}}{0{,}05 \text{ s}} = 0{,}01$
- DC (processing) = 0,01 + 0,008 = 0,018
- DC (radio + processing) = $\frac{\text{transmit time}}{\text{transmit period}} = \frac{0{,}2 \text{ ms}}{0{,}05 \text{ sec} \cdot \underset{\text{\# samples stored to transmit}}{5}} = \frac{0{,}002 \text{ sec}}{0{,}25 \text{ sec}} = 0{,}008$

Power consumption of sensor (in 1 hr):
Power consumption of processor (in 1 hr):
Power consumption of radio (in 1 hr):
Total power consumption (in 1 hr): Lifetime:
5 mAh * 0,01+ 5 uAh *0,99 =0,05+0,005 mAh = 0,055 mAh | 0,018*8 mAh + 0,982*15 uAh =0,144+0,0147 mAh = 0,1587 mAh | 0,008 *20mAh + 0,992 *20uAh = 0,16+0,0198 mAh = 0,1798 mAh

- Power consumption sensor (1 h) = 5 mAh · 0,01 + 5 µAh · 0,99 = 0,05 mAh + 0,005 mAh = $\boxed{0{,}055 \text{ mAh}}$
- Power consumption processing (1 h) = 8 mAh · 0,018 + 15 µAh · 0,982 = 0,144 mAh + 0,01473 mAh = $\boxed{0{,}15873 \text{ mAh}}$
- Power consumption radio (1 h) = 20 mAh · 0,008 + 20 µAh · 0,992 = 0,16 mAh + 0,1984 mAh = $\boxed{0{,}17984}$ mAh
- Total power consumption (1 h) = 0,055 mAh + 0,15873 mAh + 0,17984 mAh = 0,39357 mAh

Battery life = $\frac{Bat}{E} = \frac{2000 \text{ mAh}}{0{,}39357 \text{ mAh}} = 5'081{,}68$ h

Exercise 2

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photodiode on the wrist at 20 Hz
  - sampling the sensor takes 0.5 ms
  - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
  - Computing HR in the device takes 5 ms
- Transmit a data packet to the server:
  - The average time required to transmit is 2 ms
  - Requires both processor and radio active

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

Compute the energy consumption and the lifetime of the device if it computes HR itself:

- Transmits every 5 values of HR computed (1 packet every 10 seconds)

Disregard battery leaks

- Sampling at 20 Hz (sampling takes 0.5 ms, requires both processor and sensor active)
- HR is computed every 2 s (based on 40 samples), takes 5 ms
- The average time required to send a packet is 2 ms

Compute the energy consumption and the lifetime :

- Transmits every 5 values of HR computed
- 1 packet every 10 seconds

Duty cycle of sampling: Duty cycle of processing: Duty cycle of transmitting:

0,5 milliseconds (sampling time) / 0,05 seconds (sampling period)= 0,01

5 milliseconds / 2 seconds = 0,0025

2 milliseconds (transmit time) / 10 seconds (transmission period) = 0,0002

- $DC\ (\text{sampling}) : \dfrac{\text{sampling time}}{\text{sampling period}} = \dfrac{0{,}5\ ms}{\frac{1}{20}\ s} = \dfrac{0{,}5\ ms}{0{,}05\ sec} = \dfrac{0{,}0005\ sec}{0{,}05\ sec} \approx \boxed{0{,}01\ sec}$
- $DC\ (\text{processing}) = \dfrac{\text{process time}}{\text{process period}} = \dfrac{5\ ms}{2\ sec} = \dfrac{0{,}05\ sec}{2\ sec} = \dfrac{0{,}005\ sec}{2\ sec} = \boxed{0{,}0025\ sec}$
- $DC\ (\text{transmitting}) = \dfrac{\text{trans time}}{\text{trans period}} = \dfrac{2\ ms}{10\ sec} = \dfrac{0{,}002\ sec}{10\ sec} = \boxed{0{,}0002\ sec}$

Power consumption of sensor (in 1 hr): Power consumption of processor (in 1 hr): Power consumption of radio (in 1 hr):

Total power consumption (in 1 hr):

Lifetime:

5 mAh * 0,01+ 5 uAh *0,99 =0,05+0,005 mAh = 0,055 mAh

8 mAh * 0,0127+ 15 uAh *0,9873 =0,1016+0,0148 mAh = 0,1164 mAh | 0,0002 *20mAh + 0,9998 *20uAh = 0,004 + 0,02 mAh = 0,024 mAh

0,1954 mAh

2000 mAh / 0,1916 mAh = 10.235 h

- Power consumption sensor: $5\ mAh \cdot 0{,}01 + 5\ \mu Ah \cdot 0{,}99 = 0{,}05\ mAh + 0{,}0045\ mAh = \boxed{0{,}055\ mAh}$
- Power consumption processor: $8\ mAh \cdot \underbrace{0{,}0127}_{DC(\text{sample} + \text{proc.} + \text{transm.})} + 15\ \mu Ah \cdot 0{,}9873 = 0{,}1016\ mAh + 0{,}0148\ mAh = \boxed{0{,}1164\ mAh}$
- Power consumption radio: $20\ mAh \cdot 0{,}0002 + 20\ \mu Ah \cdot 0{,}9998 = 0{,}004 + 0{,}02 = \boxed{0{,}024\ mAh}$
- $E = 0{,}055\ mAh + 0{,}1164\ mAh + 0{,}024\ mAh = \boxed{0{,}1954\ mAh}$
- Battery life $= \dfrac{B_0 + L}{E} = \dfrac{2\cdot 000\ mAh}{0{,}1954\ mAh} = \boxed{10\cdot 235{,}4145\ h}$ ✓

Exercise extra-1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	0,015	mA
Radio		
current xmit	1	mA
current sleep	0,02	mA
Sensor Board		
current (full operation)	5	mA
current sleep	0,005	mA
Battery Specifications		
Capacity	2000	mAh

Consider a Mote-class sensor with the parameters in the table.
Assume that the device performs a sensing task with the following parameters:

- The sensor board is activated with a rate of 0,1 Hz to perform the sampling; this operation takes 0.5 milliseconds. At the end the sensor board is put in sleep mode. During each sensing operation the processor is always active.
- After each sampling the processor performs a computation that takes 2 milliseconds.
- Then the processor activates the radio and transmits the data. The transmission takes 1 millisecond and, during it, the processor is active. At the end the radio and the processor are both set in sleep mode.

Compute the duty cycle of each component (sensor board, radio and processor), and the lifetime of the device (assuming that the sensor stops working when its battery charge becomes 0):

Solution extra-1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	0,015	mA
Radio		
current xmit	1	mA
current sleep	0,02	mA
Sensor Board		
current (full operation)	5	mA
current sleep	0,005	mA
Battery Specifications		
Capacity	2000	mAh

- Sampling takes 0.5 ms with a rate of 0,1 Hz
- Processing: 2 ms
- Transmitting: 1 ms

Duty cycle of sampling (processor and sensors): $\frac{0{,}5\,ms}{10\,s} = \frac{0{,}0005\,s}{10\,s} = 0{,}00005$ sec

Duty cycle of processing (only processor): 0,002 s / 10 = 0,0002 sec => PROCESS = $\frac{0{,}002 + 0{,}0005 + 0{,}001}{10} = \boxed{0{,}00035}$

Duty cycle of transmissions (radio&processor): 0,001 s / 10 s = 0,0001 sec

Hence, for each component the power consumption per hour (in mAh) is:

- Sensor: 0,00005 · 5 mAh + 0,99995 · 0,005 mAh = 0,00525 mAh
- Processor: 0,00035 · 8 mAh + 0,99965 · 0,015 mAh = 0,01776 mAh
- Radio: 0,0001 · 1 mAh + 0,9999 · 0,02 mAh = 0,020098 mAh

E = 0,042848

Total consumption per hour (in mAh): 0,042848 mAh

Lifetime in hours:

$\to \frac{Batt}{E} = \frac{2000\,mAh}{0{,}042848\,mAh} \cong 46'676$ hours

✓

: transmitting:
0,00005 sensorboard: 0,0002 processor: 0,0001 radio:
0,00005 0,00035 0,0001
Duration of activity/period= 3.5 ms / 10 seconds
*note:periodis1/frequency=1/0.1=10sec
dc_idle * 0,015 mAh + dc_active * 8 mAh= (1-0.00035)*0.015 + 0.00035*8 mAh= 0,01499 + 0.0028 mAh = 0.0178 mAh
Lifetime = capacity/consumption per hour = 2000/0.043 mAh

power consumption per hour (mAh):

idle
active
total
sensor board:
0,00499975
0,00025
0,00524975
mAh
processor:
0,01499475
0,0028
0,01779475
mAh
radio:
0,019998
0,0001
0,020098
mAh
TOTAL:
0,0431425
mAh

Hence the lifetime is around 46358 hours