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LECTURE 8

Transformers & Diodes

Electromechanical Devices
MMME2051

Module Convenor – Surojit Sen

Learning Outcomes

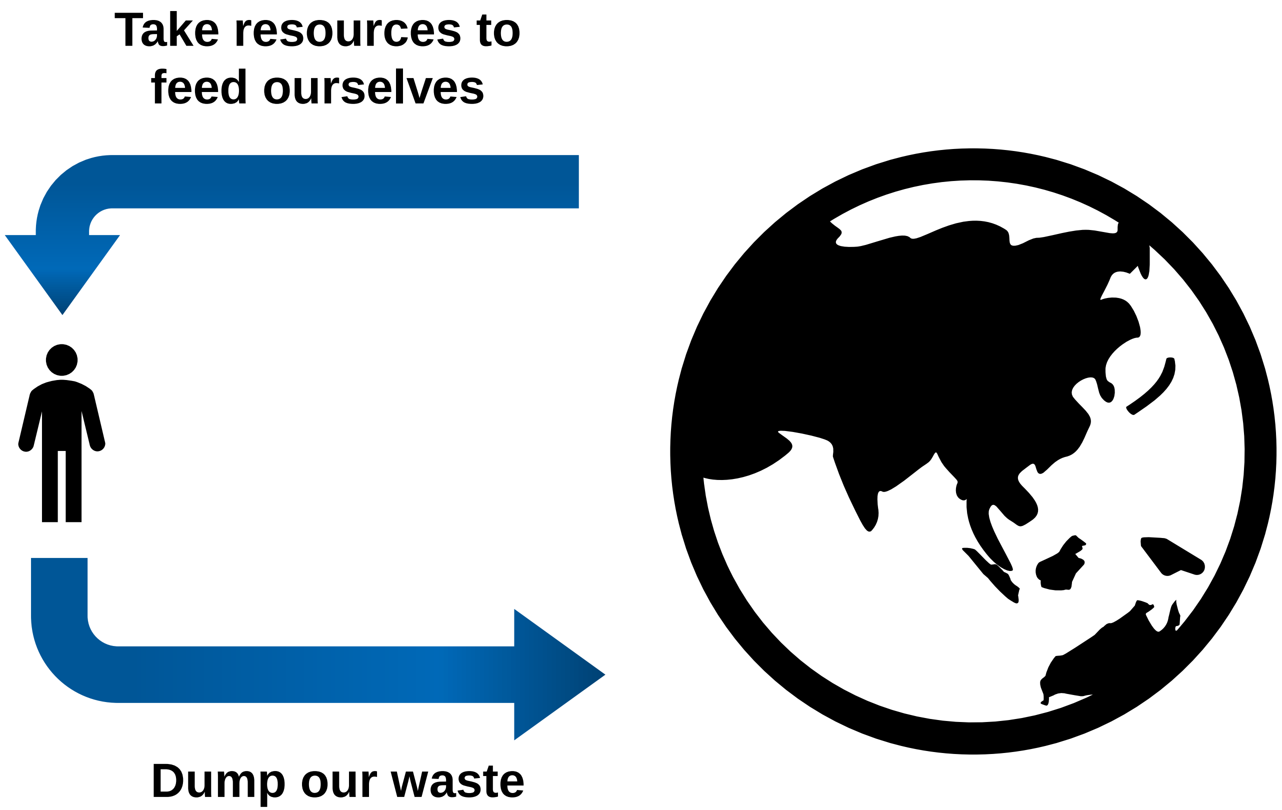
- **Sustainability Development Goals @UoN**
- Transformers
  - **Electromagnetic induction**
  - Analogy to **gears**
  - **Referred impedance**
- **Diodes**
  - AC to DC – Rectification
  - DC Ripple on Rectifier Output

Sustainable Development Goals (SDGs)

https://www.youtube.com/watch?v=qfOgdj4Okdw

Why should we be sustainable?

- This is exactly what animals do
- **Assumption** is – Earth is an **bottomless source and sink**
- Worked great when we started – **not true any more**!
- **Earth's capacity is declining** – to provide resources as well as to absorb waste
- Being Sustainable means we should consider the **£ associated with extracting & dumping**



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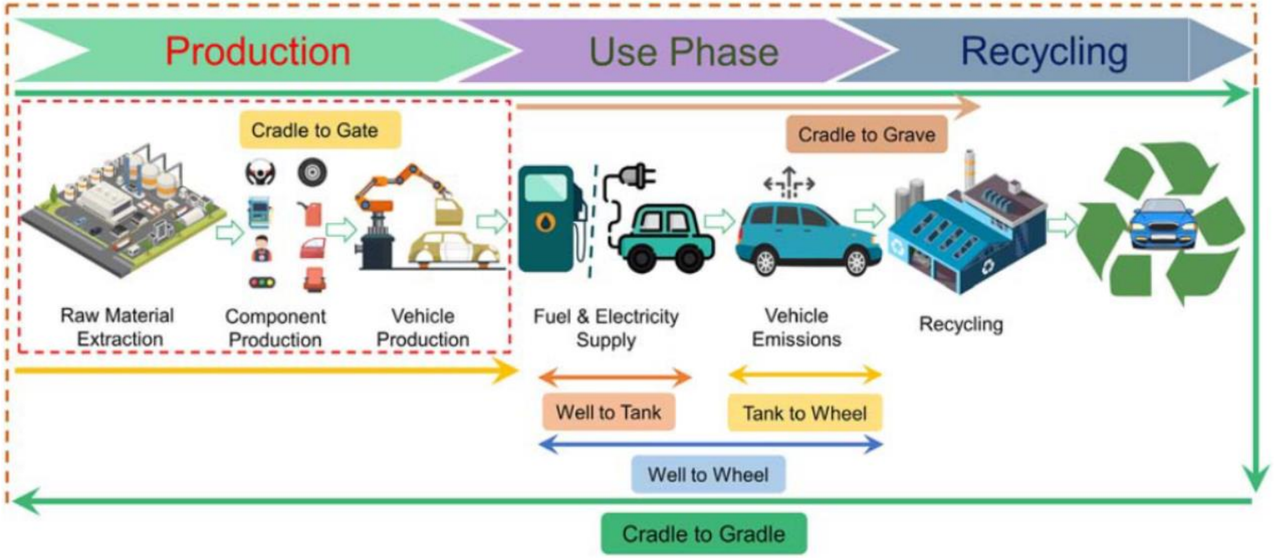
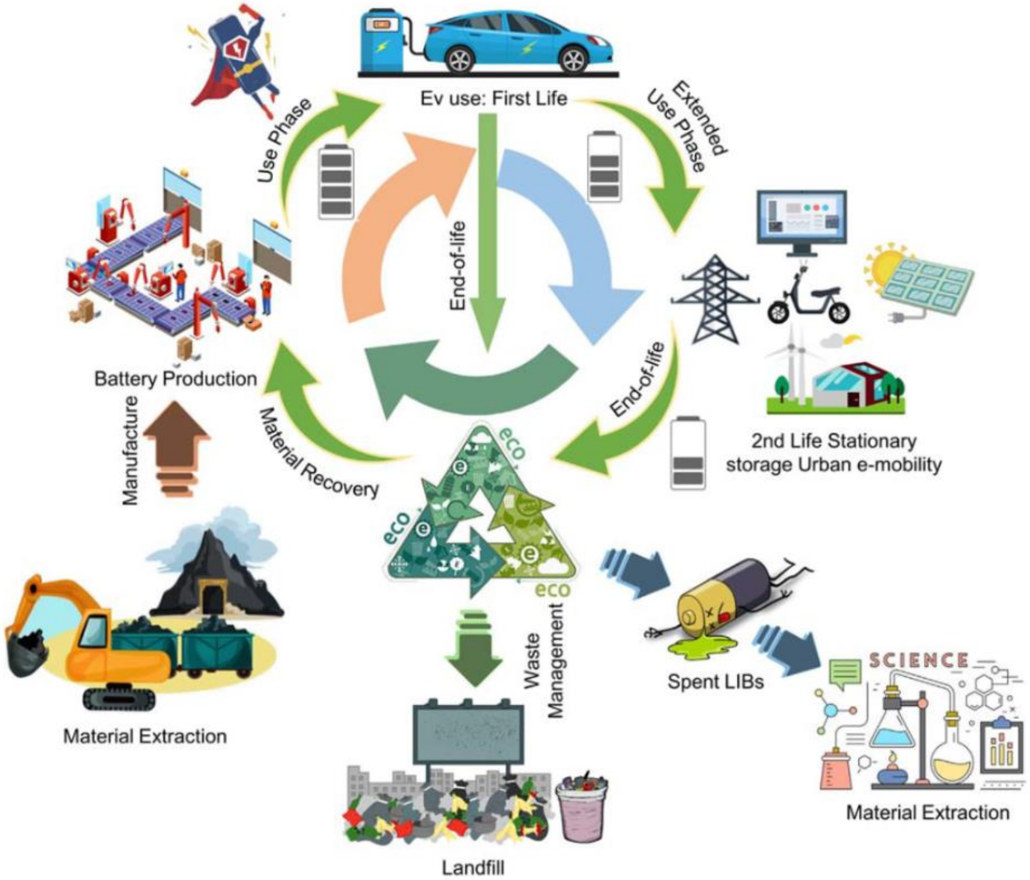
Sustainable Development Goals (SDGs)

1. No poverty
2. Zero hunger
3. Good health and wellbeing
4. Good quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure
10. Reduced inequalities
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice and strong infrastructure
17. Partnerships for good

Sustainable Development Goals (SDGs)

How am I contributing?



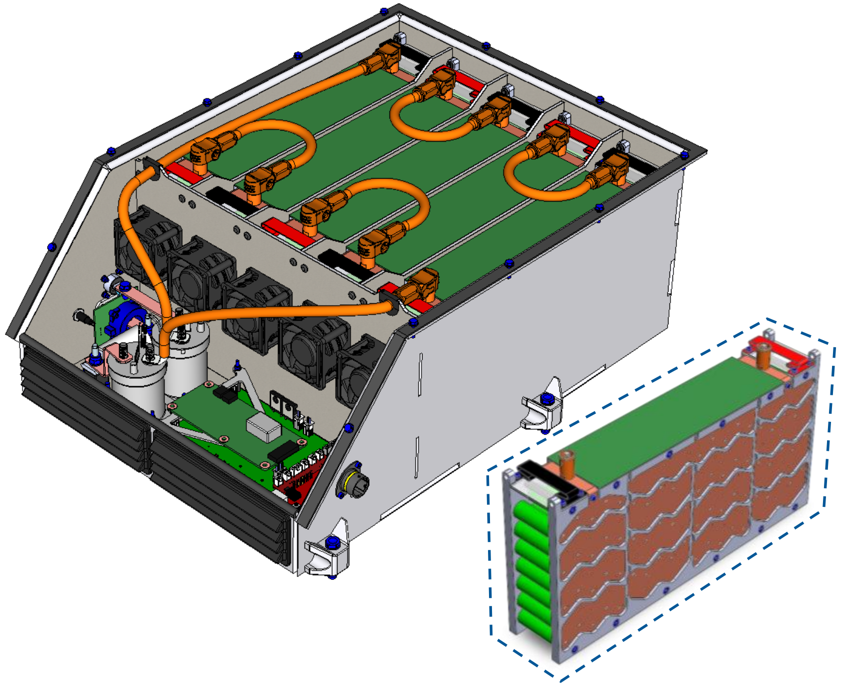


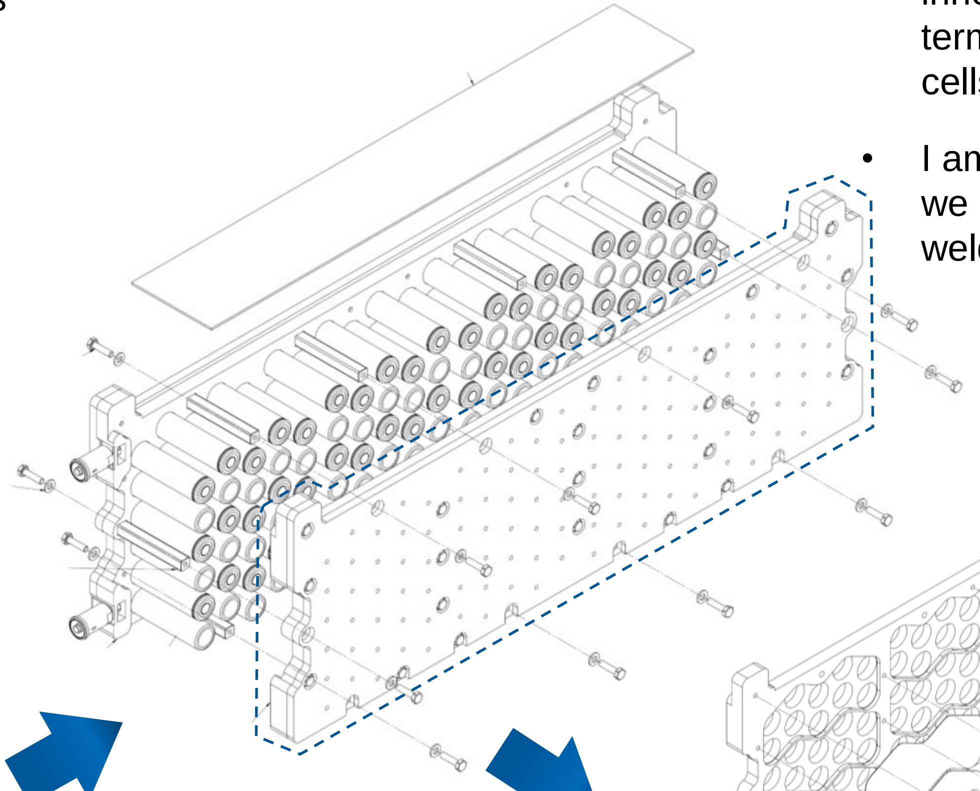
Source:
Xiaoning Xia, Pengwei Li, A review of the life cycle assessment of electric vehicles: Considering the influence of batteries, Science of The Total Environment, Volume 814, 2022, 152870, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.152870.
(https://www.sciencedirect.com/science/article/pii/S0048969721079493)

Sustainable Development Goals (SDGs)

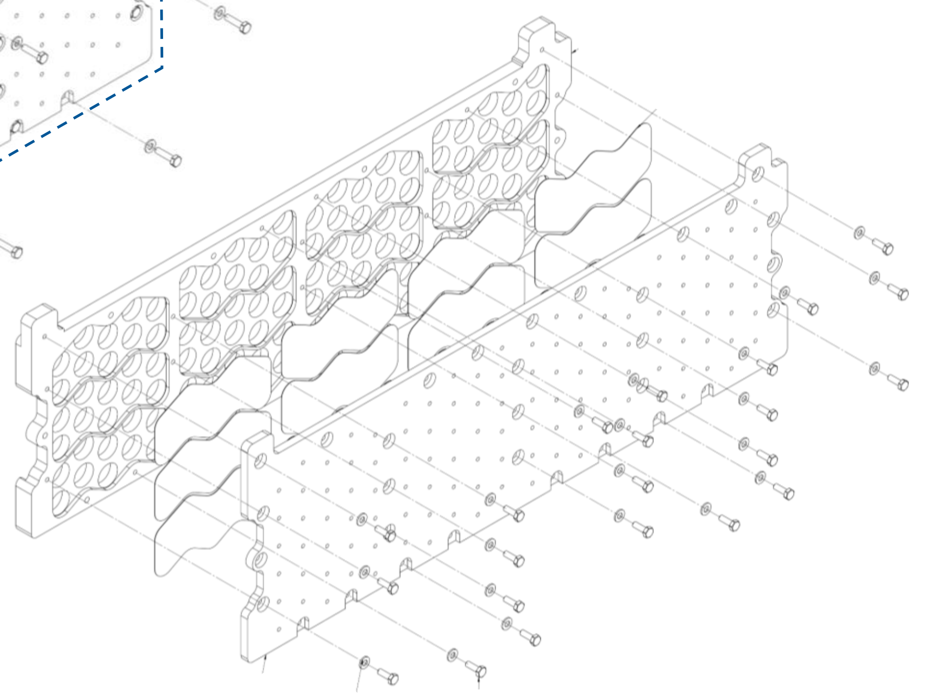
How am I contributing?

- Normal EV battery is made of multiple modules
- Cells in module tied together by copper plates welded to terminals
- Reliable – but no repairable or reusable
- Only way to recycle is to crush and chemically extract minerals





- By eliminating the “weld” feature, batteries inherently are sustainable – increase life term, swap faulty batteries, use degraded cells in domestic power applications
- I am researching on the effects of this – can we make a battery pack (without any welding) that is reliable?



Learning Outcomes

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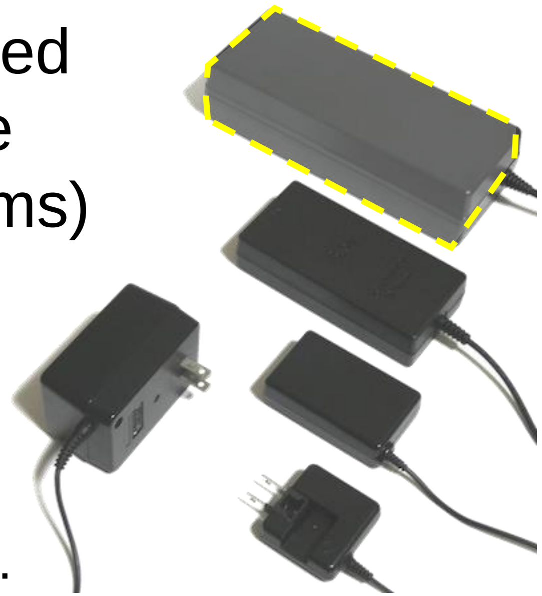
Transformers

A **transformer** is used to convert AC at one voltage (say 150 Vrms) to another (say 50 Vrms)

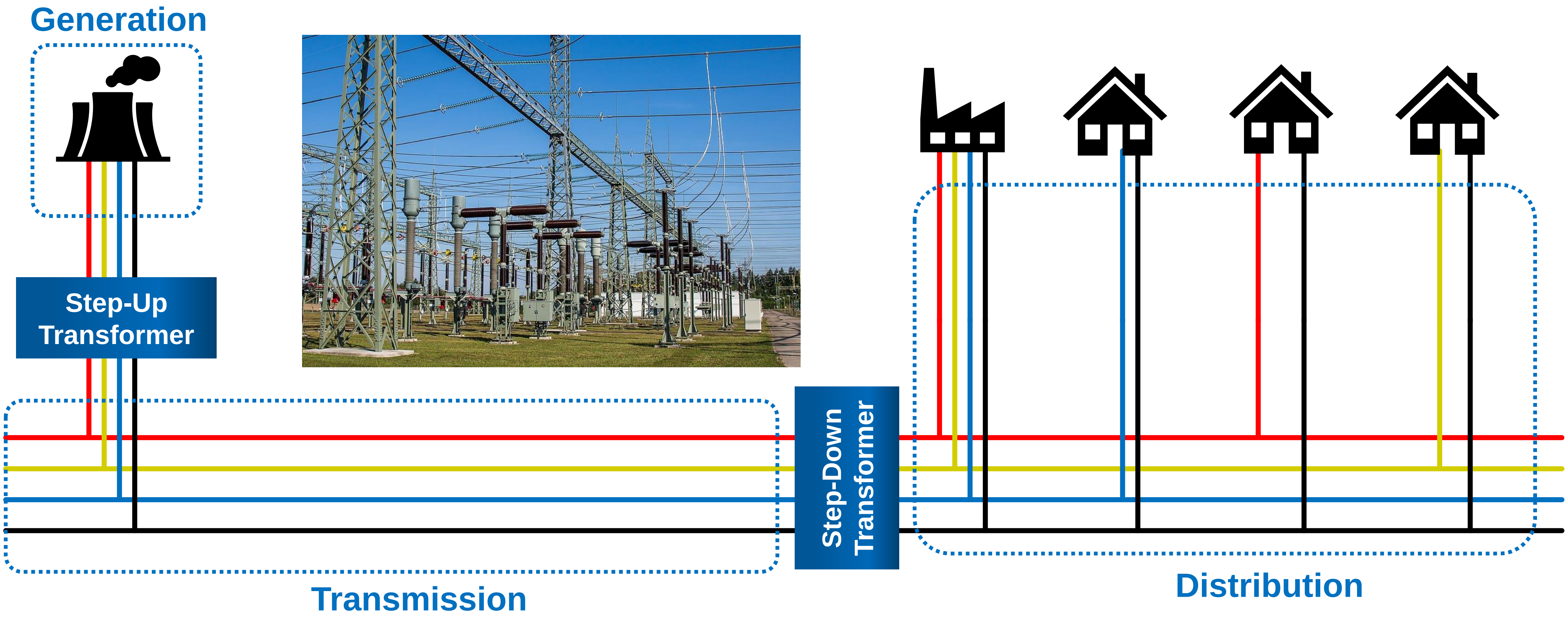


Transformer

Lets take a laptop charger:

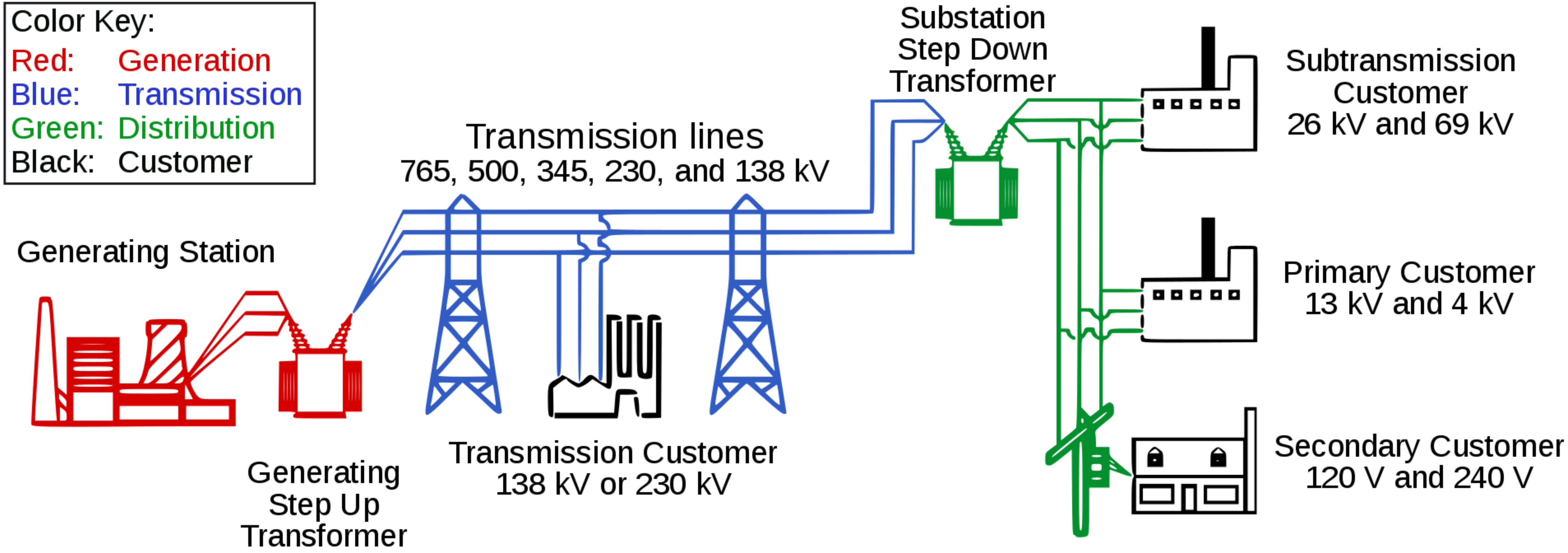
- Battery is likely 8-12V DC
- Wall socket 240 Vrms needs to be converted to 8-12V DC to charge the battery
- The first step in this process is to **step-down** the 240 Vrms to ~10Vrms (which eventually gets converted to DC using "rectifier" – we shall study that too, but later)

Transformers



Transmission is always done at very high voltage (10s-100s of mega volts!) to **reduce copper losses**, i.e., $E = i^2R$, if we reduce i we can reduce E (heat loss); as $P = vi$, we have to increase v to keep transmitting same amount of power

Transformers



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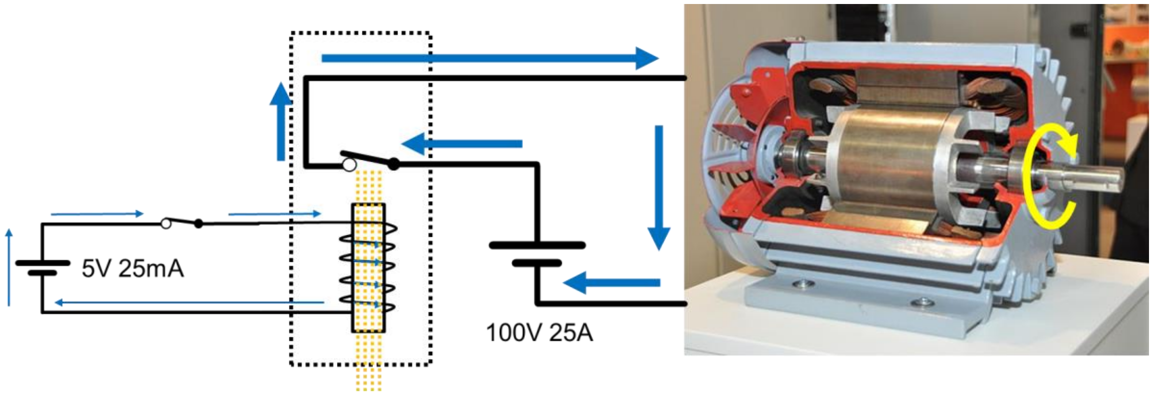
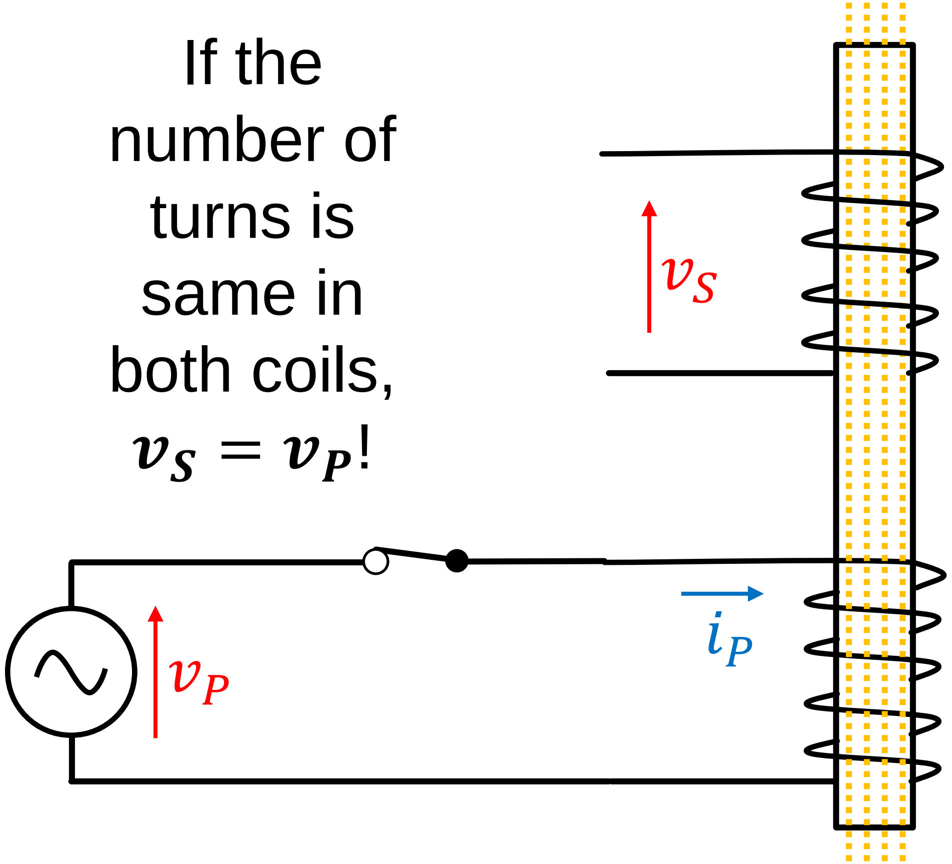
How does it work?

Remember the electrical relay (or electric switch) we studied earlier



If the number of turns is same in both coils, $\boldsymbol{v_S = v_P}$!



- A **current-carrying coil** produces a **magnet inside the core**
- What is interesting to note is that the **reverse phenomenon is also true**, i.e., if you are able to magically generate magnetic “lines” inside a core, current would be induced in the coil wrapped around it!

Transformers

$$v_P = L\frac{di_P}{dt}$$

We know that this derivative action is caused by magnetic **"flux"** (the green dotted lines shown) and **magnetic energy**. Without delving into maths, we can rewrite the equation to relate voltage and flux:

$$v_P = n_P\frac{d\phi}{dt}$$

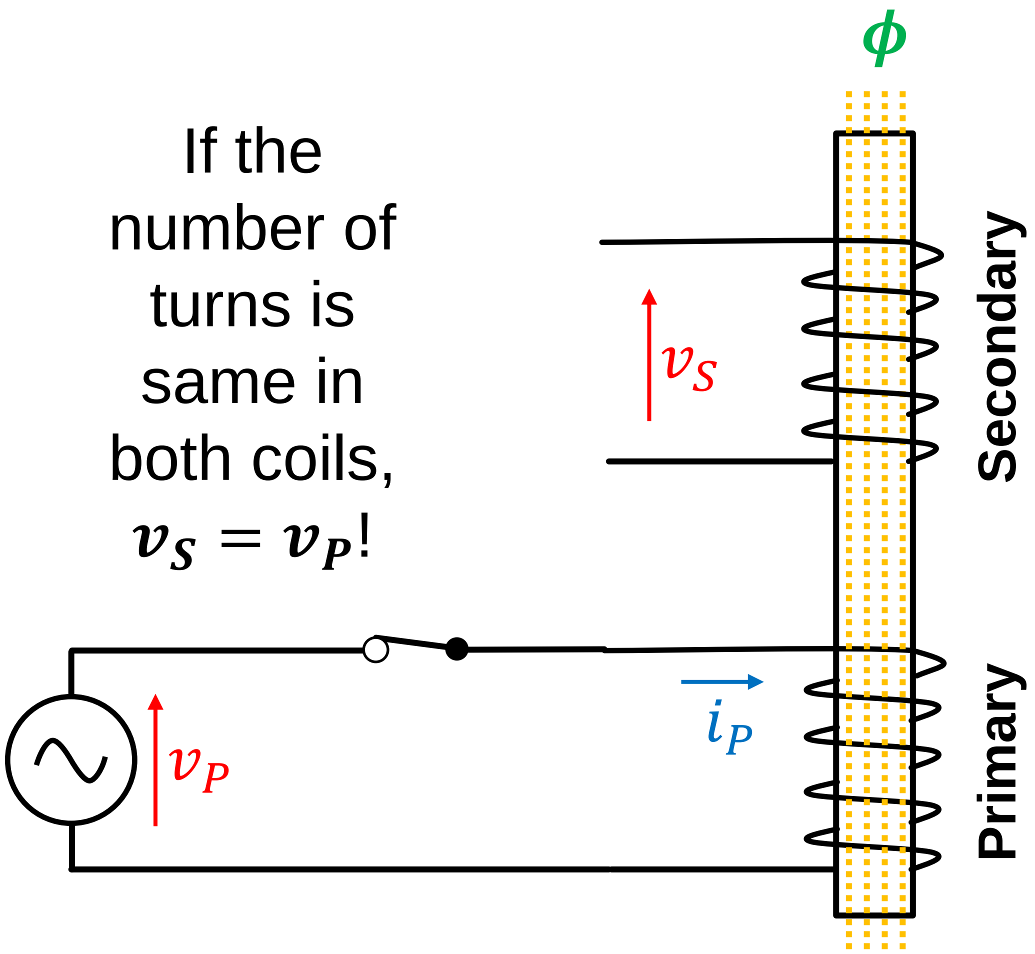
Same rules applies on secondary side:

$$v_S = n_S\frac{d\phi}{dt}$$

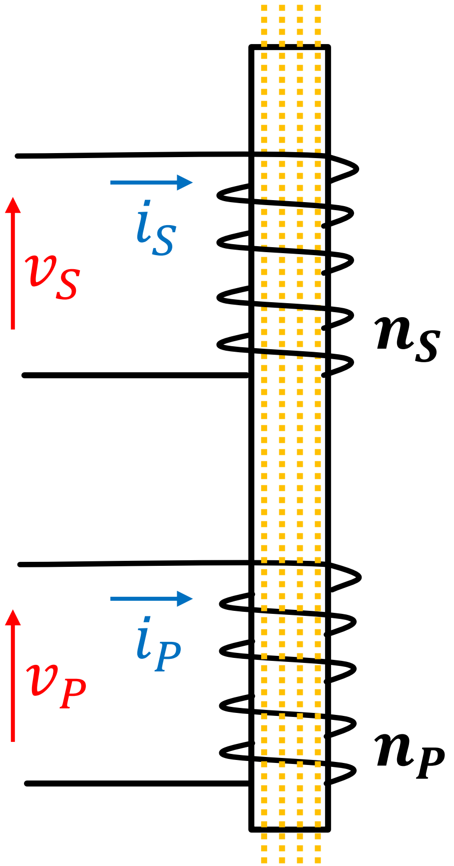
As ϕ is same, we can re-write:

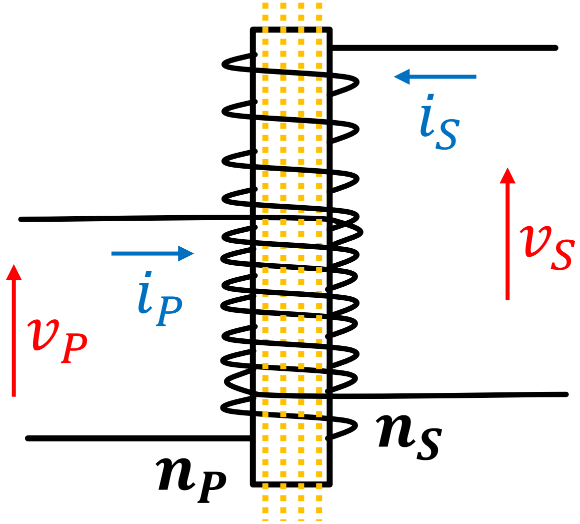
$$\frac{\boldsymbol{v_P}}{\boldsymbol{v_S}} = \frac{\boldsymbol{n_P}}{\boldsymbol{n_S}} = \textbf{turns ratio}$$

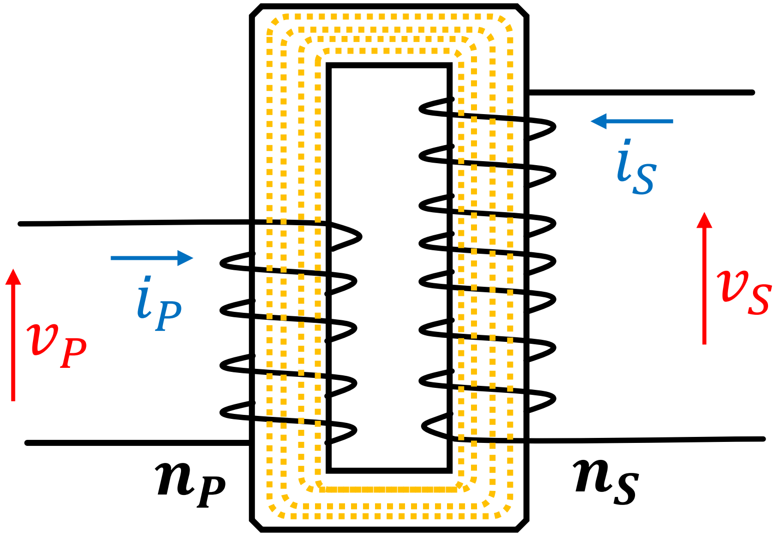
If the number of turns is same in both coils, $\boldsymbol{v_S = v_P}$!



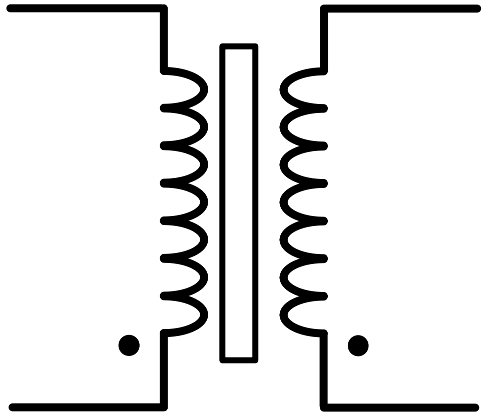
Transformers







Symbol of an "Isolation Transformer"



- The dot indicates polarity
- Usually defined as "A transformer has a ratio of 125:45" – this is the number of turns on primary and secondary respectively

Transformers

We know that:

$$\frac{v_P}{v_S} = \frac{n_P}{n_S} = \text{turns ratio}$$

Let us connect the secondary side with a generic load with impedance Z

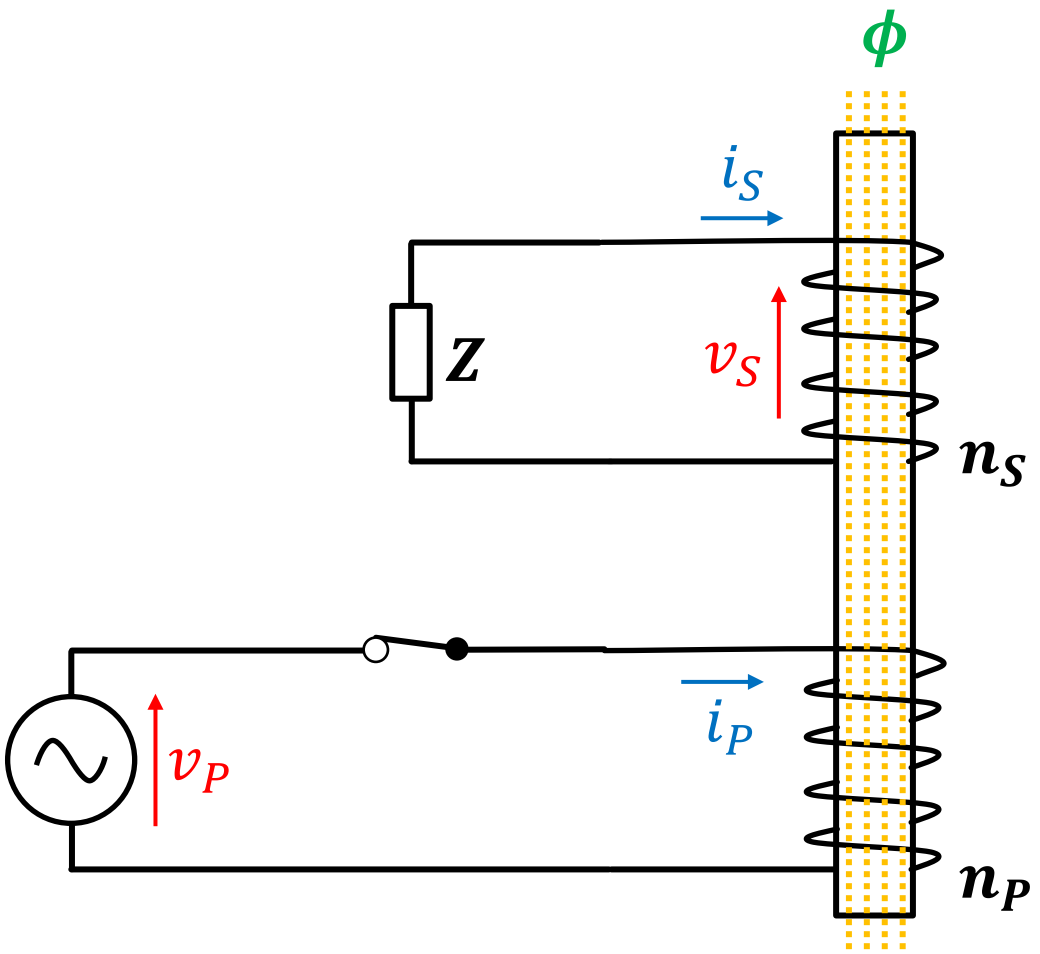
The transformer cannot create or destroy power (most transformers are almost 100% efficient):

$$P_P = P_S$$

$$v_P i_P = v_S i_S$$

$$\frac{i_P}{i_S} = \frac{n_S}{n_P} = \frac{1}{\text{turns ratio}}$$

Current follows the opposite relation to conserve energy

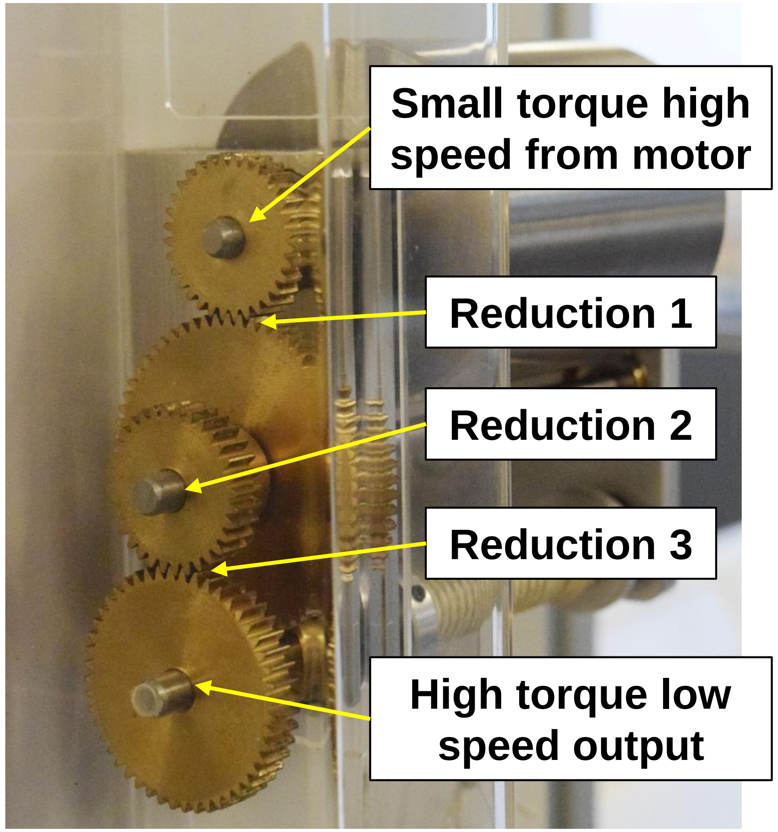


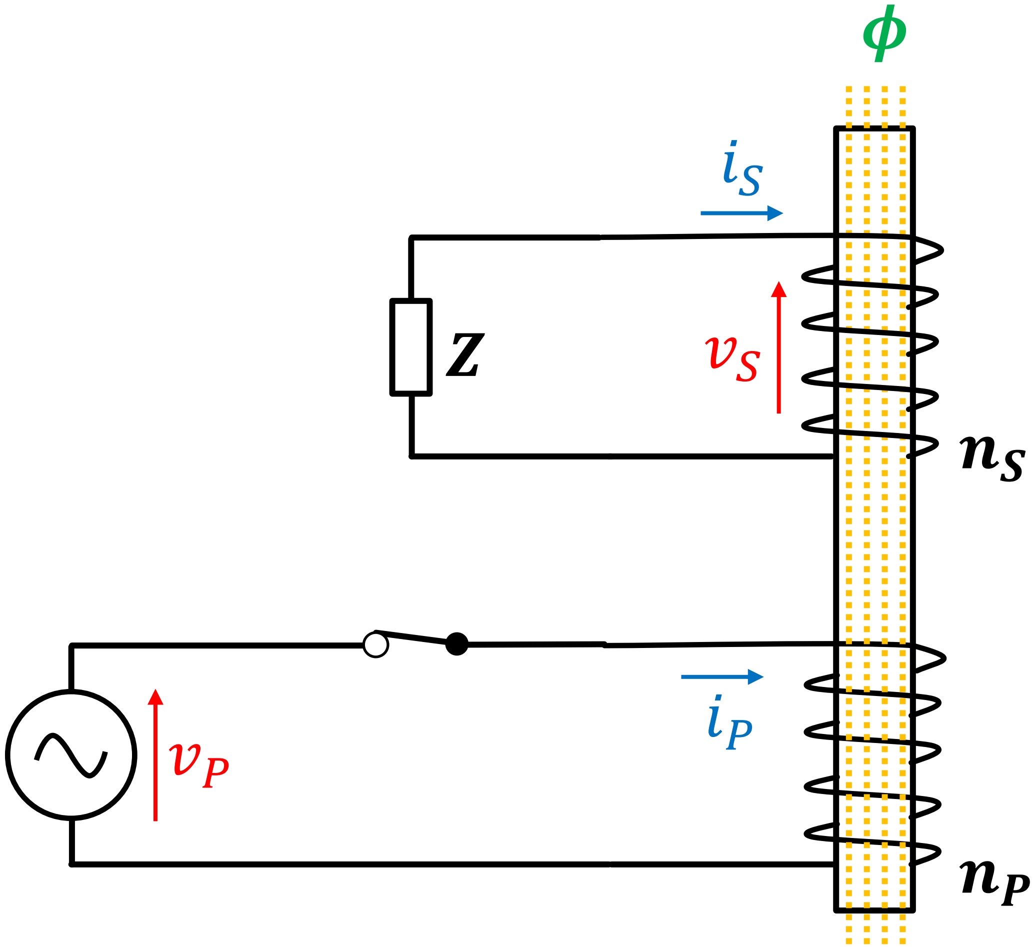
Transformers

Does this remind you of gears?

Gearbox converts between **speed** and **torque** (product remains same as GB cannot create/destroy energy as well)

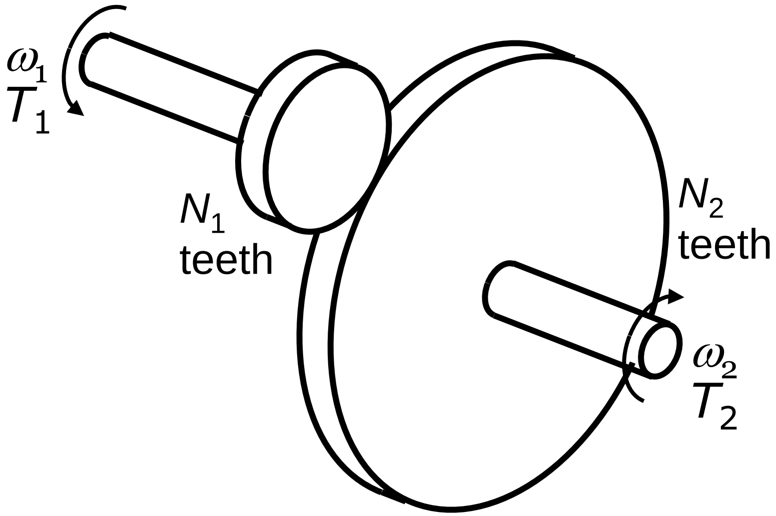
Transformer is an **electric gearbox**





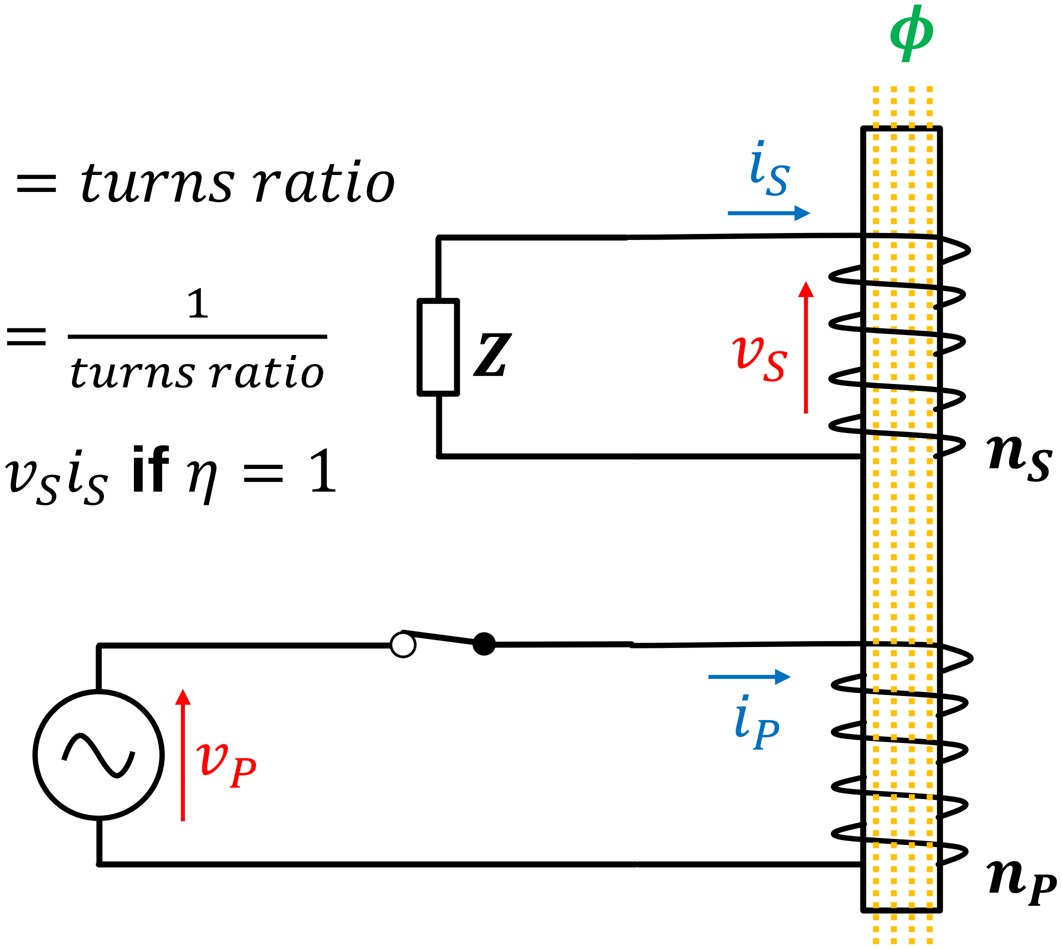
Transformers

Does this remind you of gears?



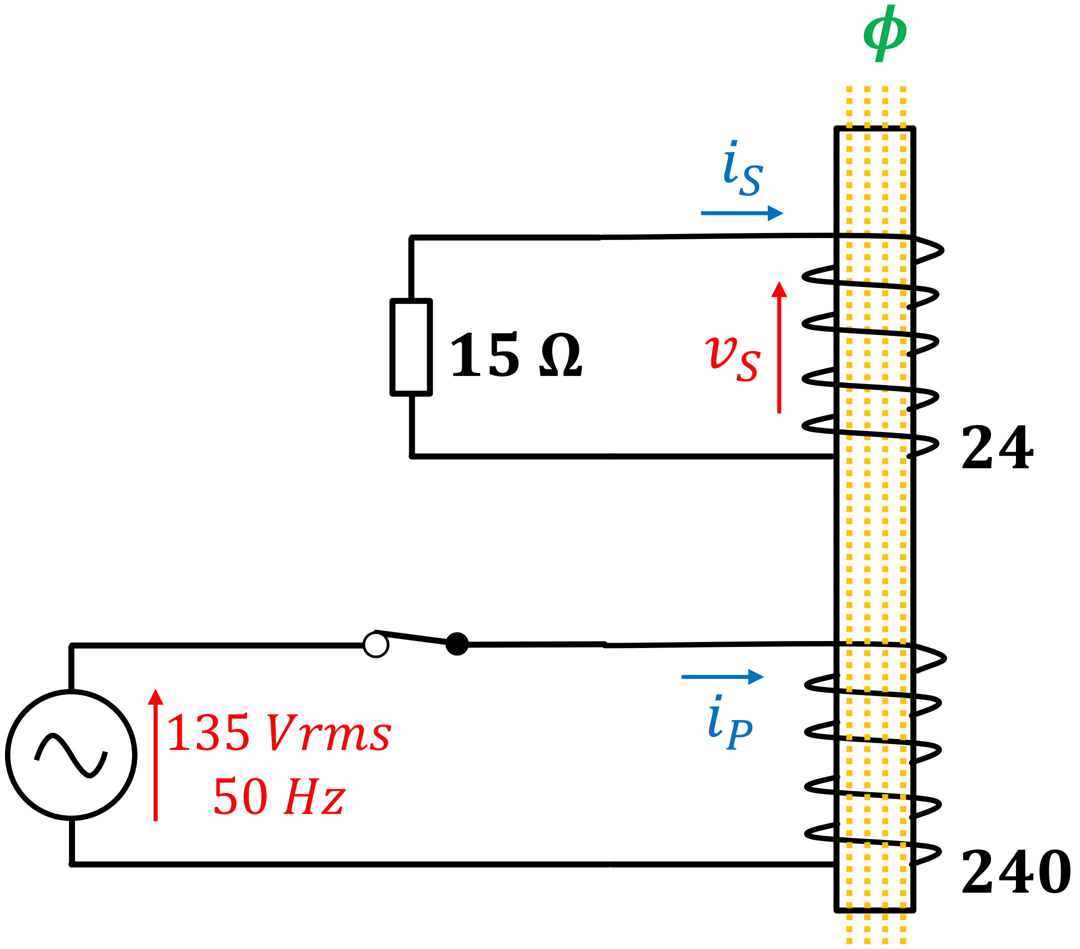
- $\frac{T_2}{T_1} = \frac{N_2}{N_1} = teeth\,ratio$
- $\frac{\omega_2}{\omega_1} = \frac{N_1}{N_2} = \frac{1}{teeth\,ratio}$
- $T_1\omega_1 = T_2\omega_2$ **if** $\eta = 1$

- $\frac{v_P}{v_S} = \frac{n_P}{n_S} = turns\,ratio$
- $\frac{i_P}{i_S} = \frac{n_S}{n_P} = \frac{1}{turns\,ratio}$
- $v_P i_P = v_S i_S$ **if** $\eta = 1$



Let us now look at referred impedance using a worked example

- A transformer has a ratio of 240:24.
- It is supplied from a 135V (rms) 50 Hz supply and supplies a 15Ω load
- What are the secondary voltage and current?
- What are the primary voltage and current?
- What value of resistance appears to be across supply?



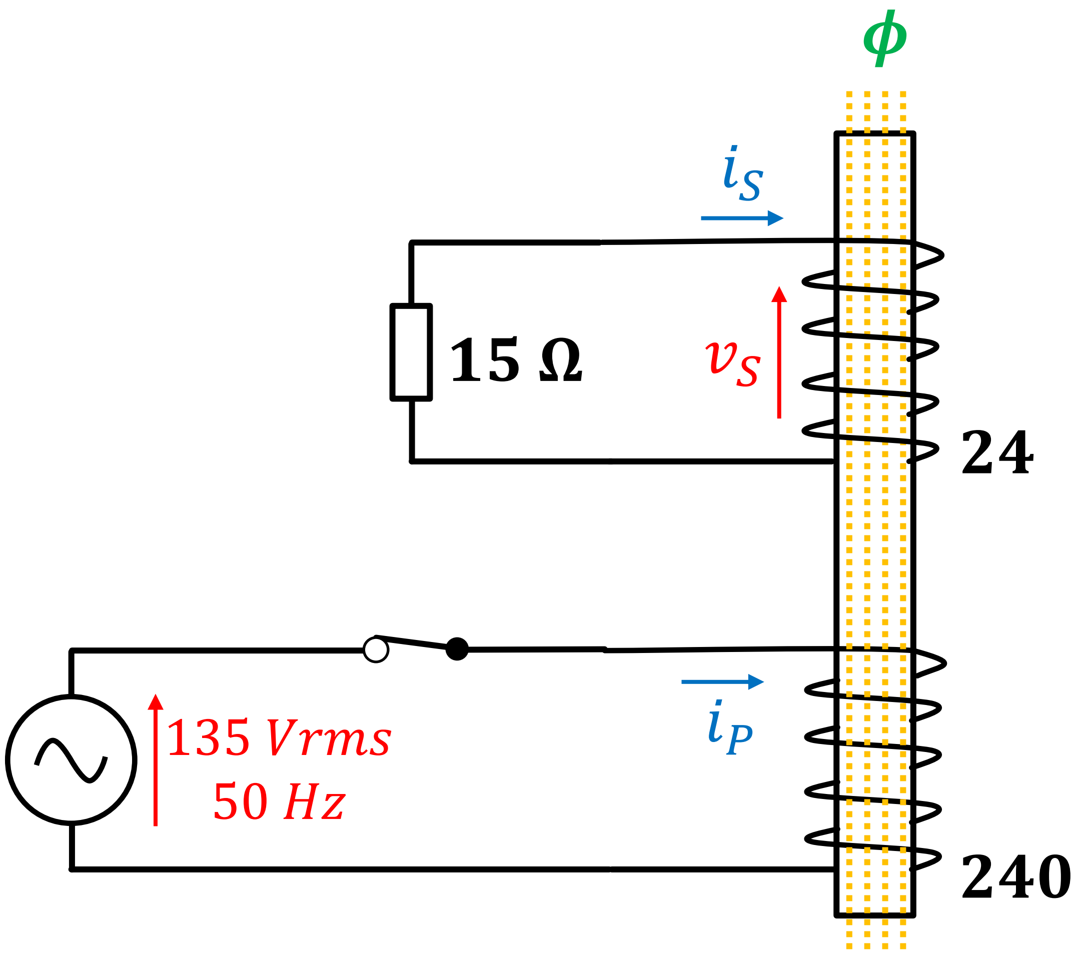
Let us now look at referred impedance using a worked example

$$Turns\ ratio = \frac{n_P}{n_S} = \frac{240}{24} = 10$$

$$v_S = \frac{1}{10} \times v_P = \frac{1}{10} \times 135 = 13.5\ Vrms$$

$$i_S = \frac{v_S}{Z} = \frac{13.5}{15} = 0.9 Arms$$

$$i_P = \frac{1}{10} \times i_S = 0.09\ Arms$$



Put yourself in the shoes of the power supply – you are supplying 135Vrms to an unknown load which is drawing 0.09Arms current

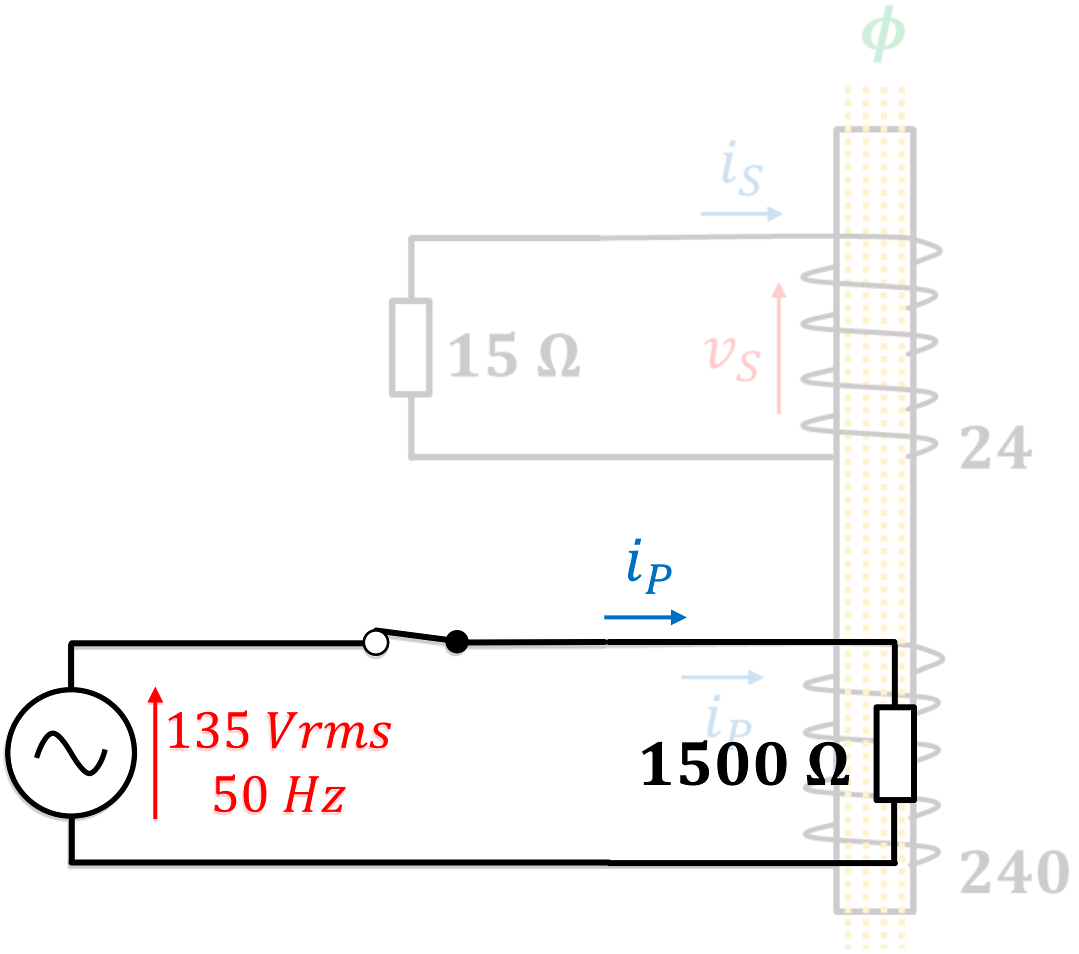
Let us now look at referred impedance using a worked example

Put yourself in the shoes of the power supply – you are supplying 135Vrms to an unknown load which is drawing 0.09Arms current

$$Z_P = \frac{v_P}{i_P} = \frac{135}{0.09} = 1500\Omega$$

This is called the **Referred Impedance** – the 15Ω impedance on the secondary side is "as seen" from the primary side

$$\frac{Z_P}{Z_S} = \left(\frac{n_P}{n_S}\right)^2 = \textbf{square of turns ratio}$$



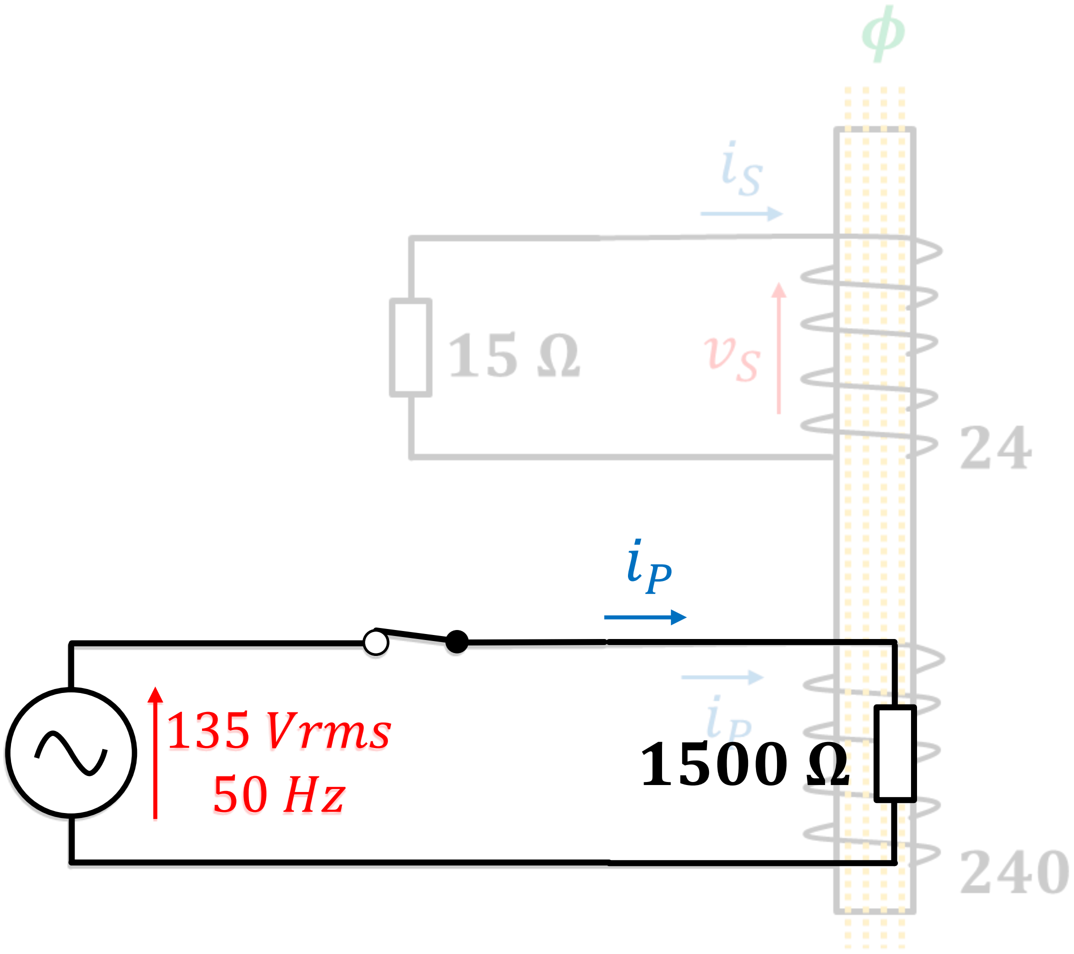
Let us now look at referred impedance using a worked example

$$\frac{Z_P}{Z_S} = \left(\frac{n_P}{n_S}\right)^2 = \text{square of turns ratio}$$

Think about it this way:

$$Z_P = \frac{v_P}{i_P}$$

- **Current on the primary side**, caused by
- **Current on secondary side**, caused by
- **Voltage on secondary side**, caused by
- **Voltage on primary side**



Referred Impedance: worked example

- A dynamics experiment requires an electromagnetic shaker. You have found one: $Z = 56 + j100\ \Omega$
- It needs amplifier to drive it but the only one you can find is a hi-fi amplifier for a load of around 8Ω, not designed for this shaker.
- Can you match them and do the experiment?

Referred Impedance: worked example

Find magnitude & argument of impedance:

$$56 + j100 = \sqrt{562 + 1002}\angle\tan^{-1}\frac{100}{56}$$

$$= 115\Omega\angle61°$$

Now choose a transformer so that the magnitude of the **referred impedance is** $\approx \mathbf{8\Omega}$

$$\frac{Z_P}{Z_S} = \left(\frac{n_P}{n_S}\right)^2 = \frac{8}{115} = 0.07$$

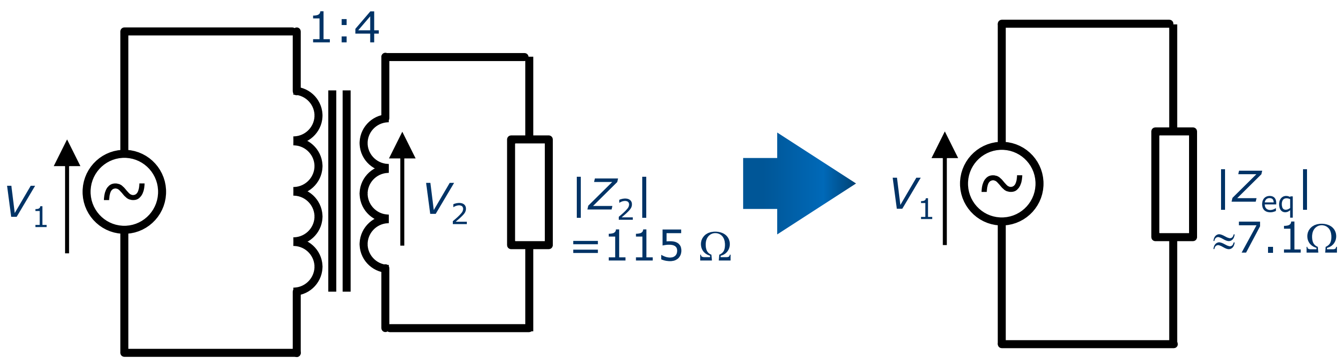
$$\frac{n_P}{n_S} = \sqrt{0.07} = 0.26 \approx \frac{1}{4}$$

If we chose a transformer with 1:4 turns ratio:

$$Z_P = \left(\frac{1}{4}\right)^2 (56 + j100)$$

$$Z_P = 3.5 + j6.25$$

$$Z_P = 7.1\Omega\angle61°$$



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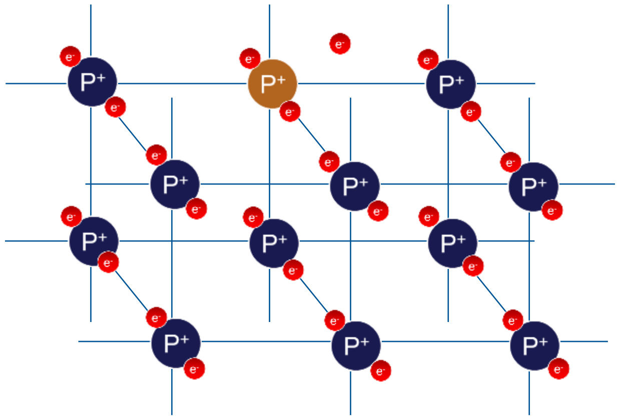
Diodes

Doping – control how much “semi” conduction happens!

Pure semiconductors (called “intrinsic”) are often intentionally doped by a specific impurity (order of few parts per million) to alter its electrical properties (called “extrinsic”)

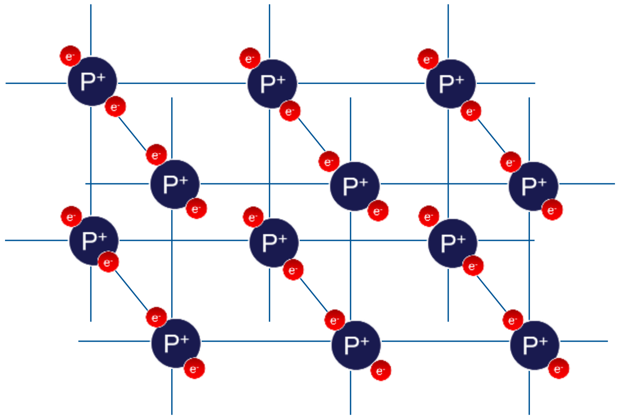
N-type Doping

Group V elements of periodic table (electron donor) are infused into the lattice structure of silicon that donate an electron



Phosphorus
Arsenic
Antimony

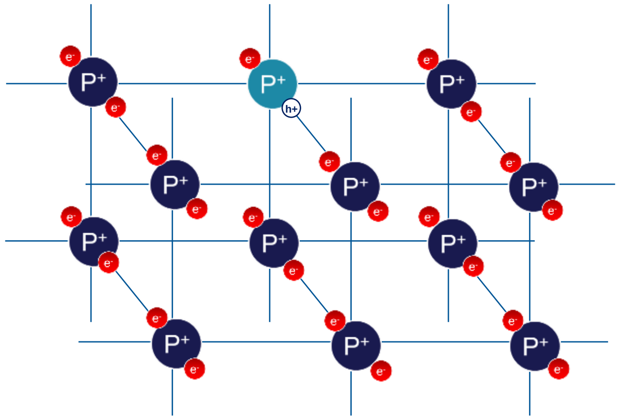
Silicon



Boron
Aluminium
Gallium

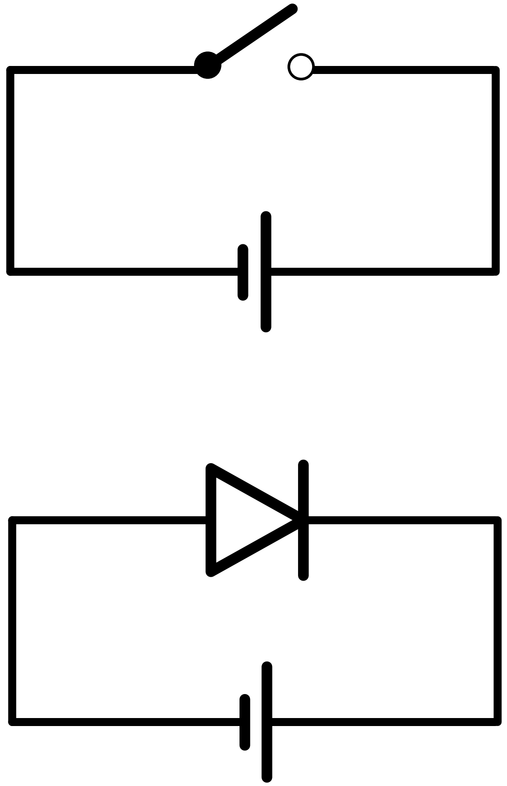
P-type Doping

Group III elements of periodic table (electron acceptor) are infused into the lattice structure of silicon that an electron

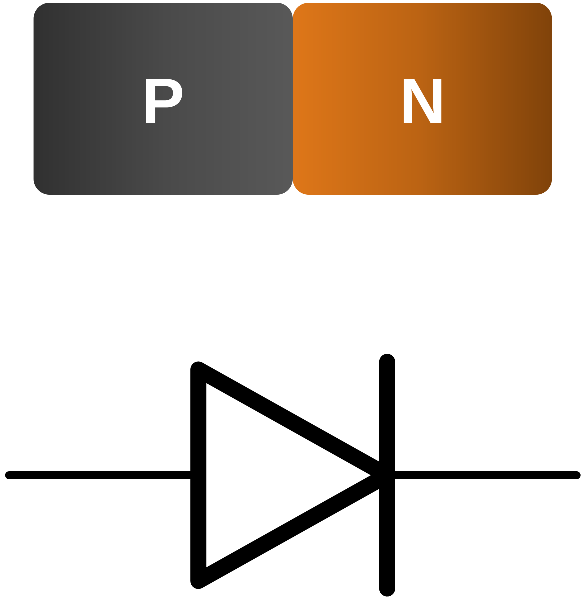


PN Junction (Diode)

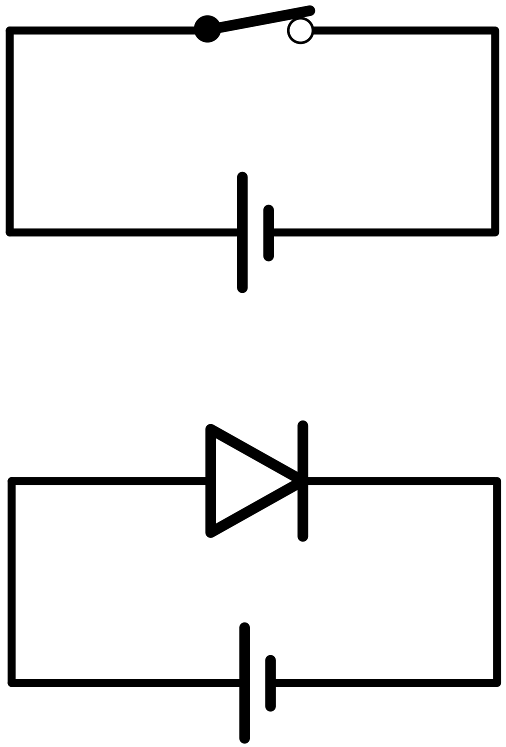
Basic building block of all electronics – one-way valve



Reverse Bias



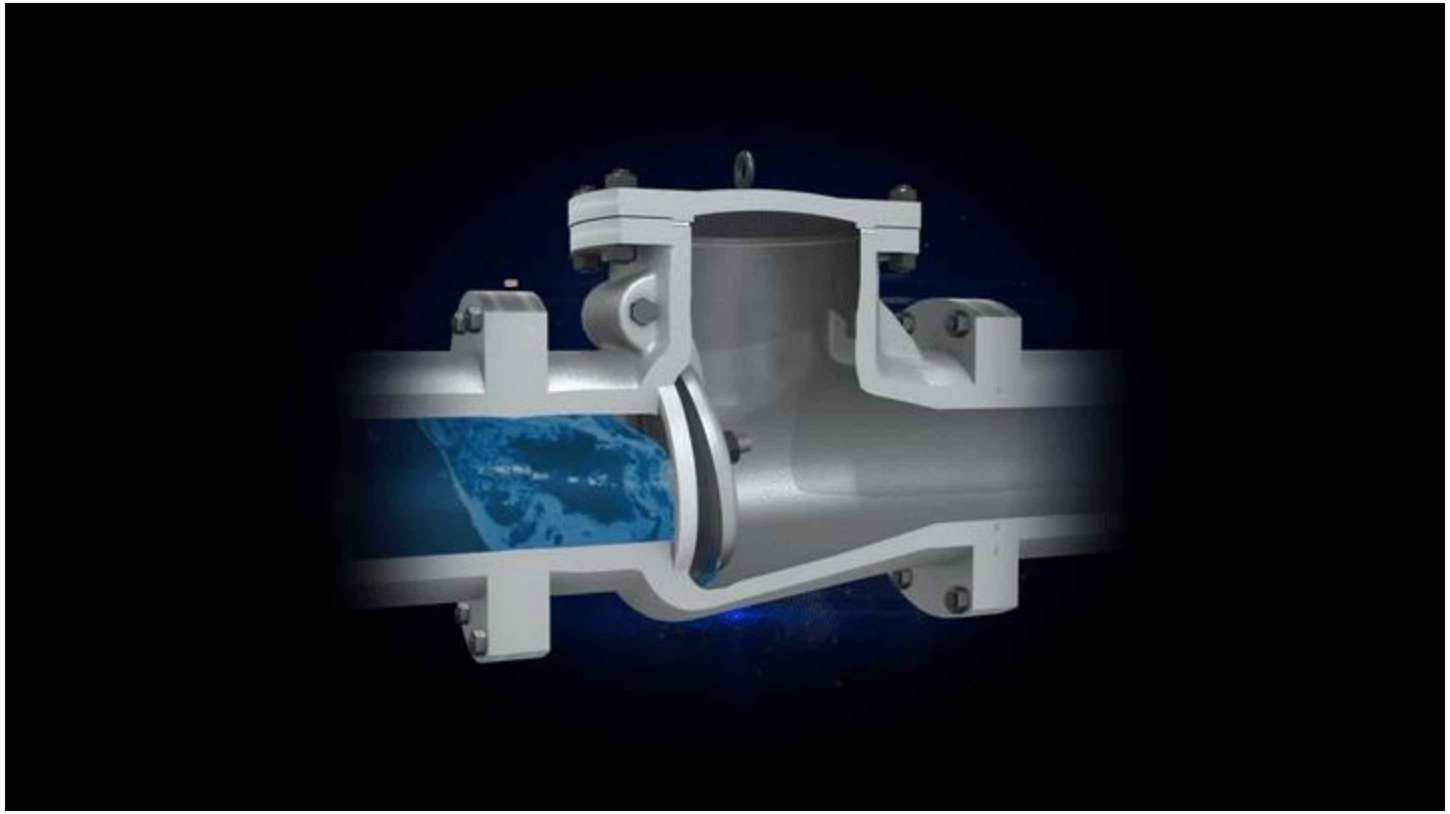
Diode



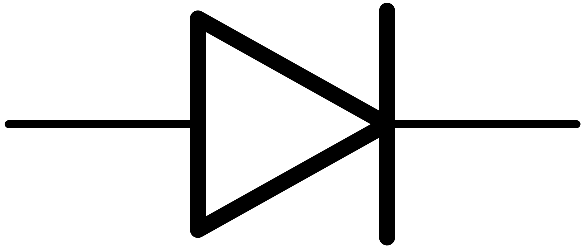
Forward Bias

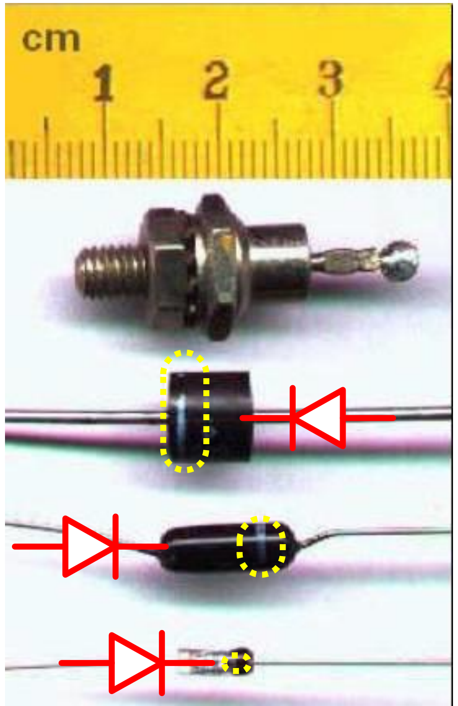
Diodes

Diode is like a one-way valve – it allows current to flow in only the “forward” direction, and blocks in “reverse” direction

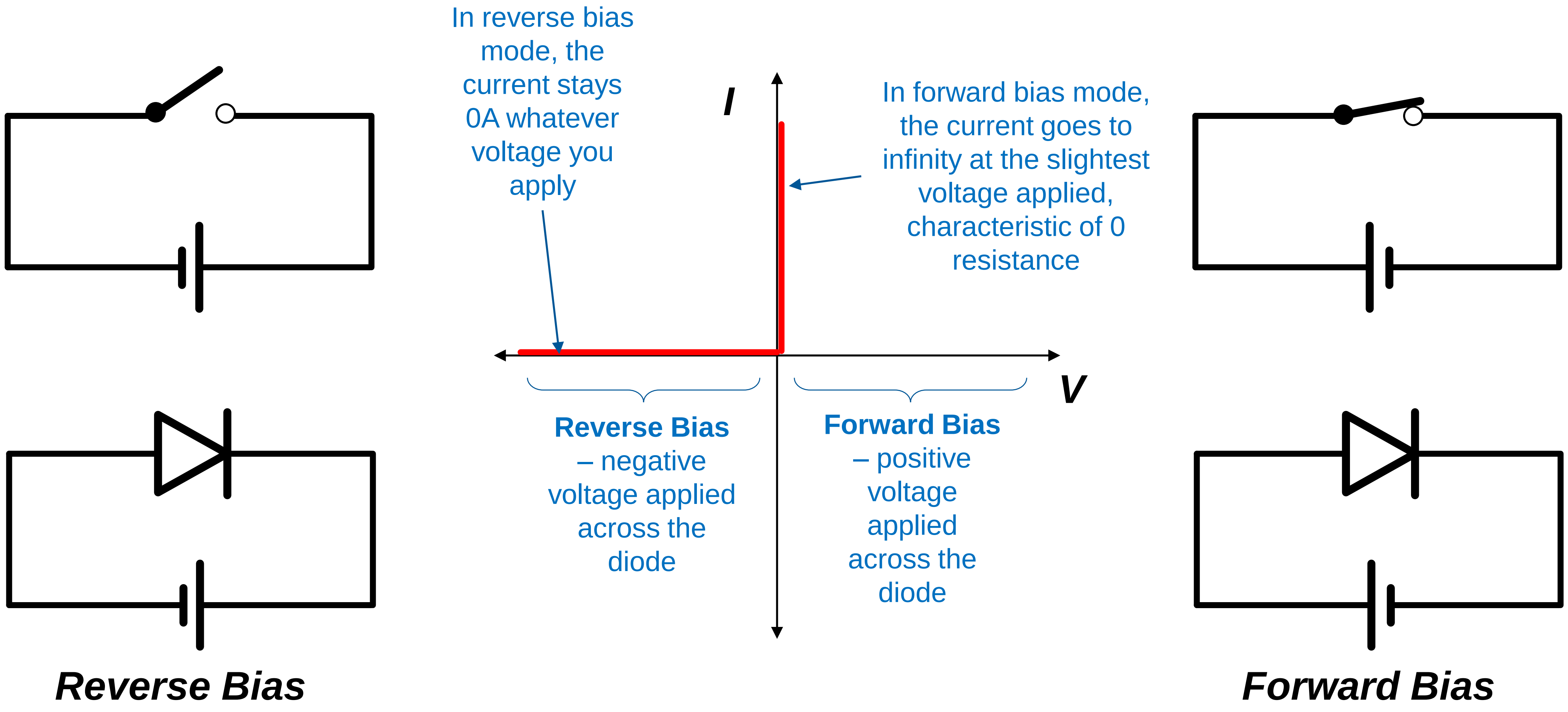


Swing Check Valve Animation - G M Engineering (www.gmengg.com)





Ideal Diode Characteristic

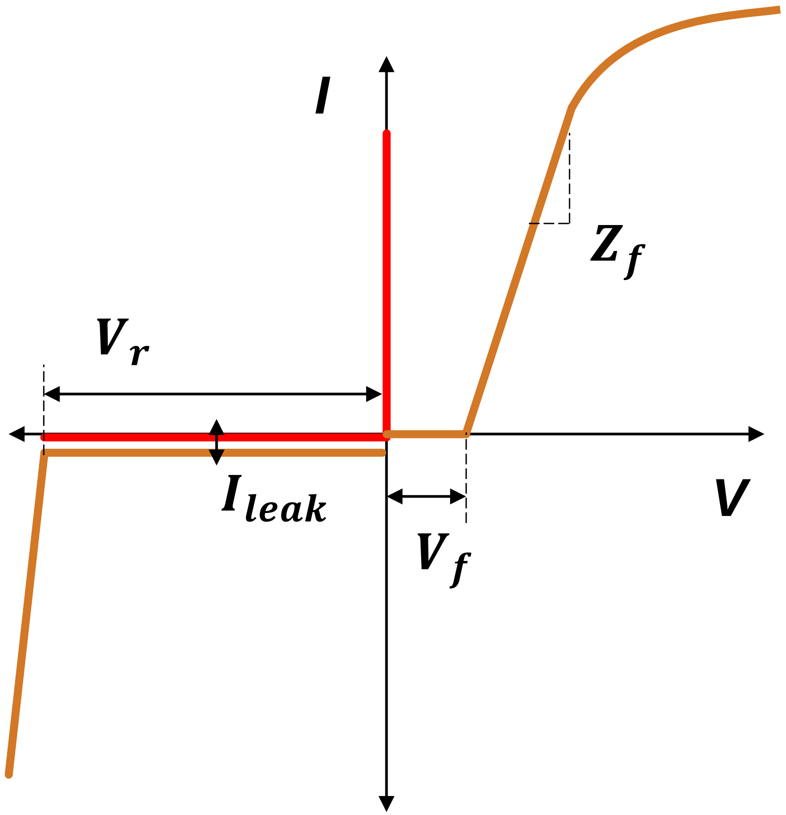


Diodes

Real Diode Characteristic

DC Blocking Voltage (range of 1 Volts to several kilovolts depending on application) – Similarly, a real diode cannot continue to "block" reverse bias voltage indefinitely, it "gives up" after this voltage is reached

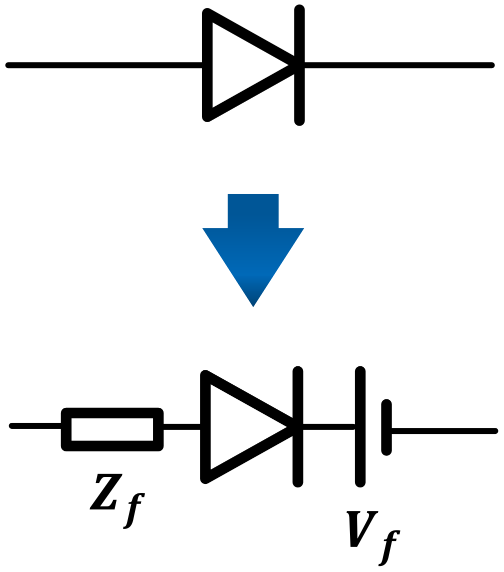
Reverse Leakage Current (few μA) – A real diode allows very little current to flow when reverse biased. This is a highly non-linear region



Forward Bias Impedance (few μΩ to mΩ depending on device application) – The device performs as a "very low resistance" device until it reaches saturation, when it becomes non-linear

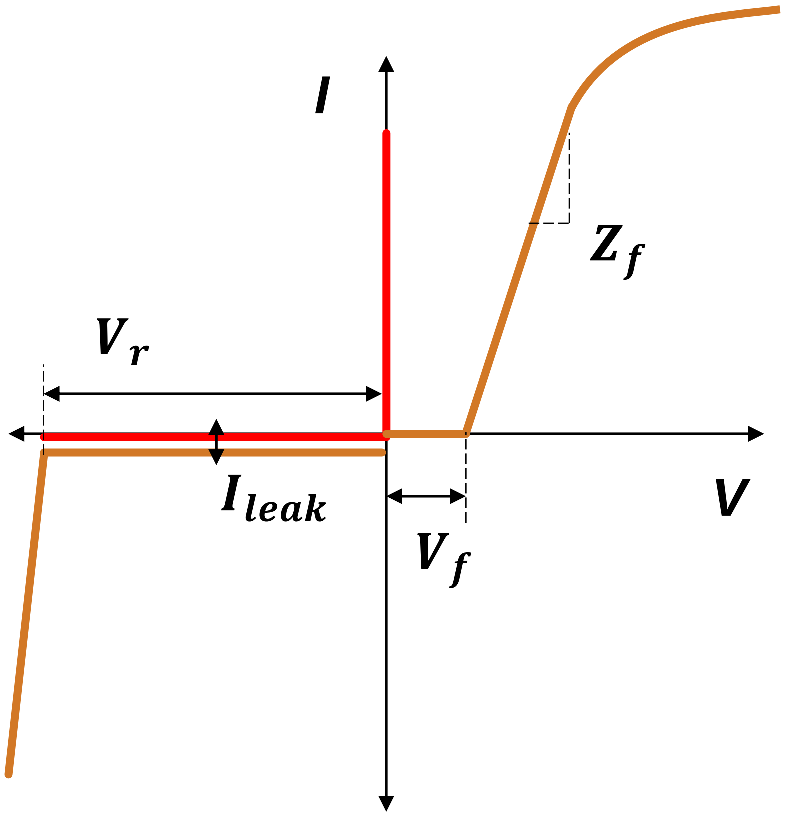
Forward Voltage ($0.1V$ to $1V$ depending on material) – The device is forward biased "after a threshold voltage" - not instantaneously zero voltage

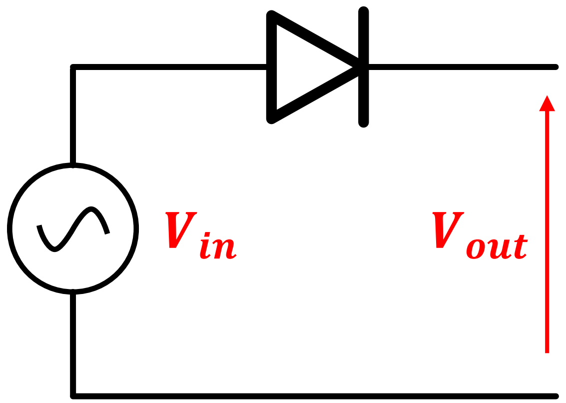
Real Diode Characteristic

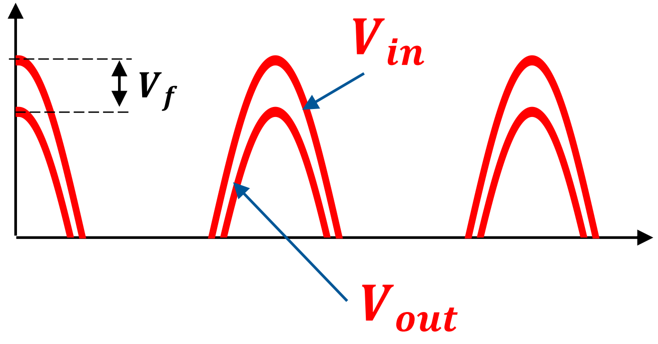


Forward Bias

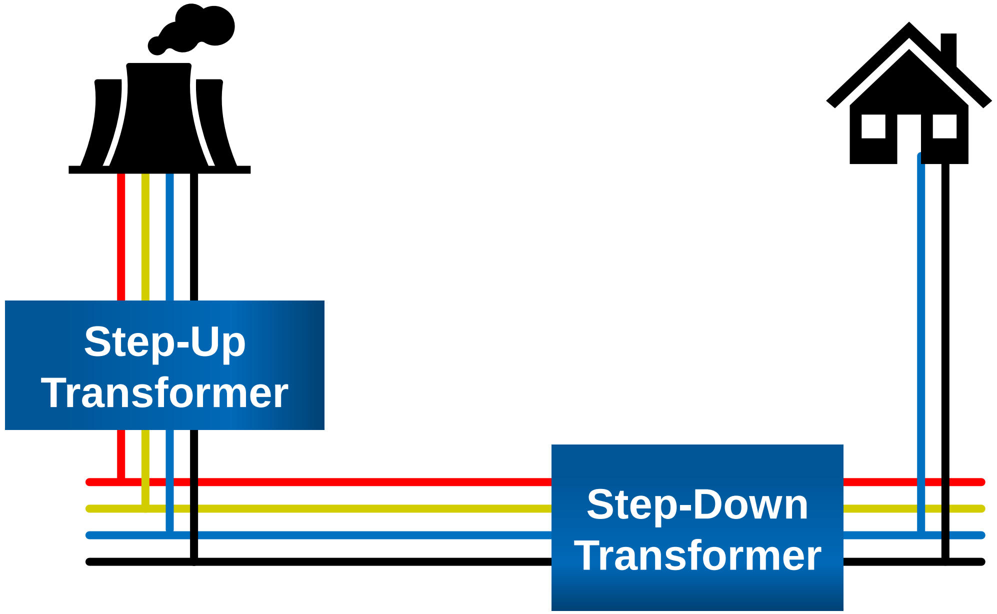
There is no simple way to draw the non-linear arrangement in reverse bias

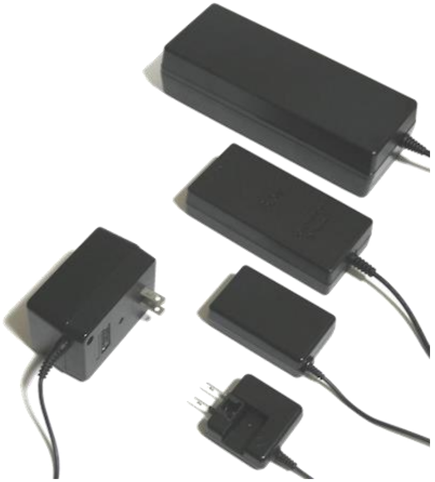


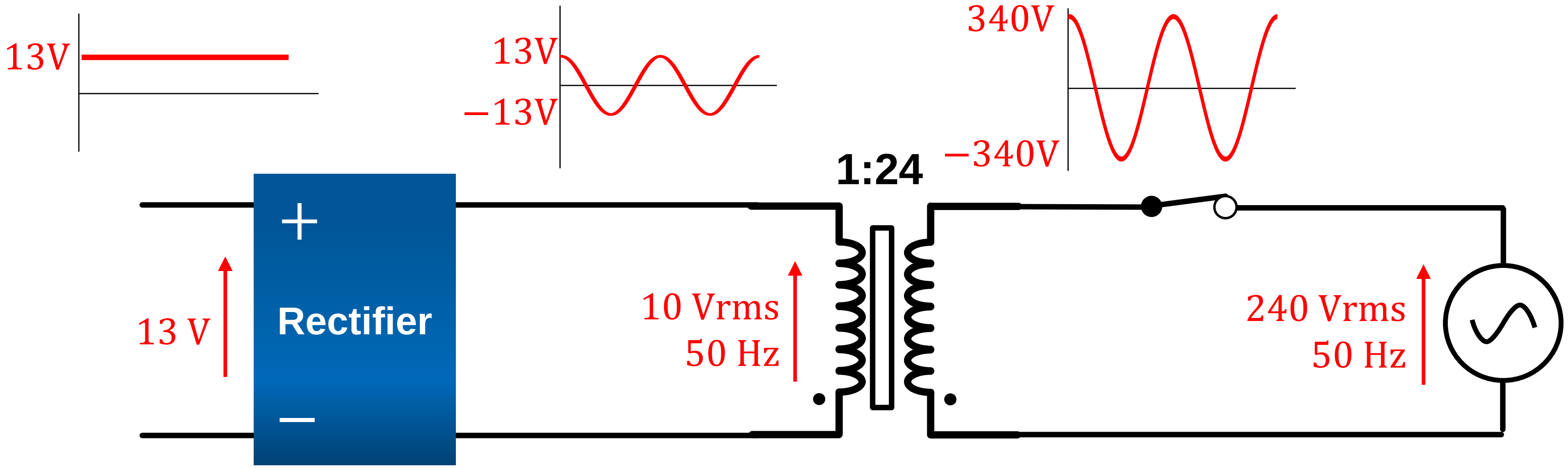




AC to DC – Rectification

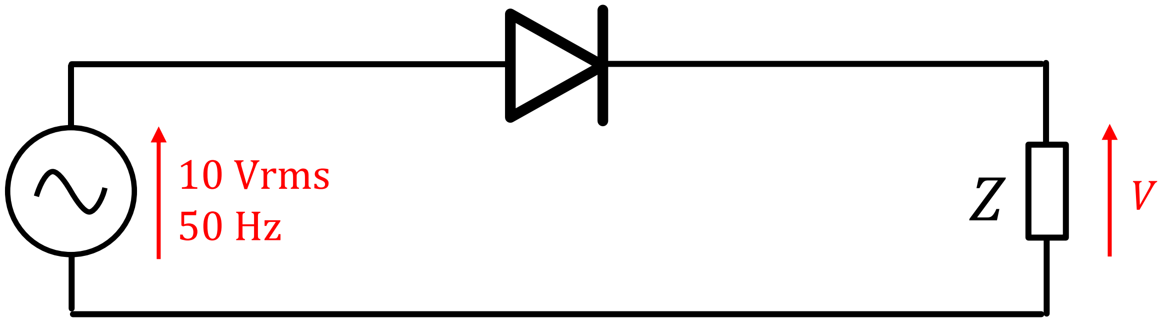




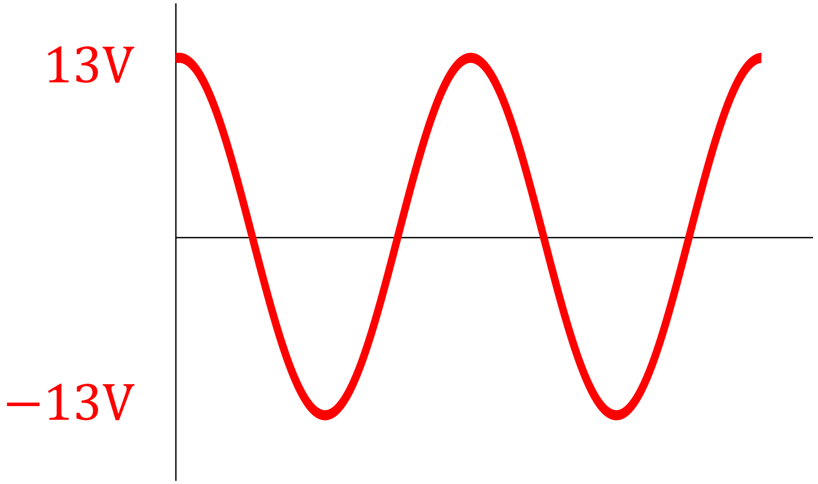


AC to DC – Rectification

Let us assume the input is post-transformer…

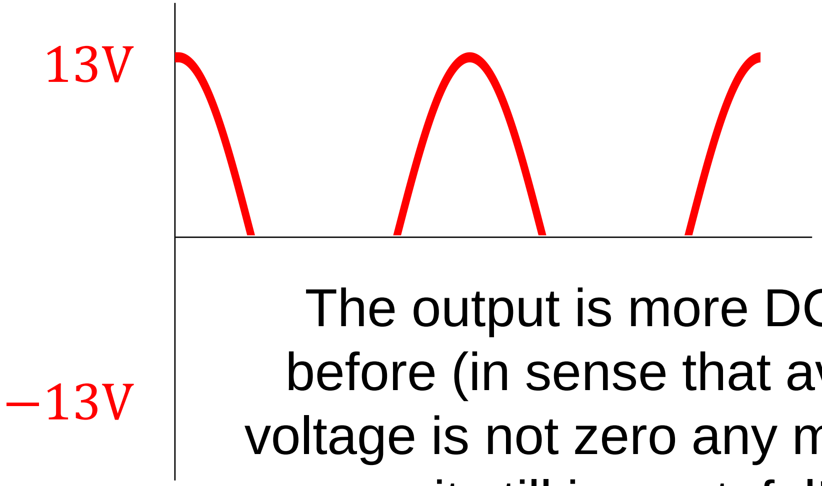


We would ideally like to **invert the negative half-cycle**!



The diode is forward biased only in the **positive half-cycle** of the AC waveform

In **negative half-cycle**, the diode breaks/disconnects the circuit

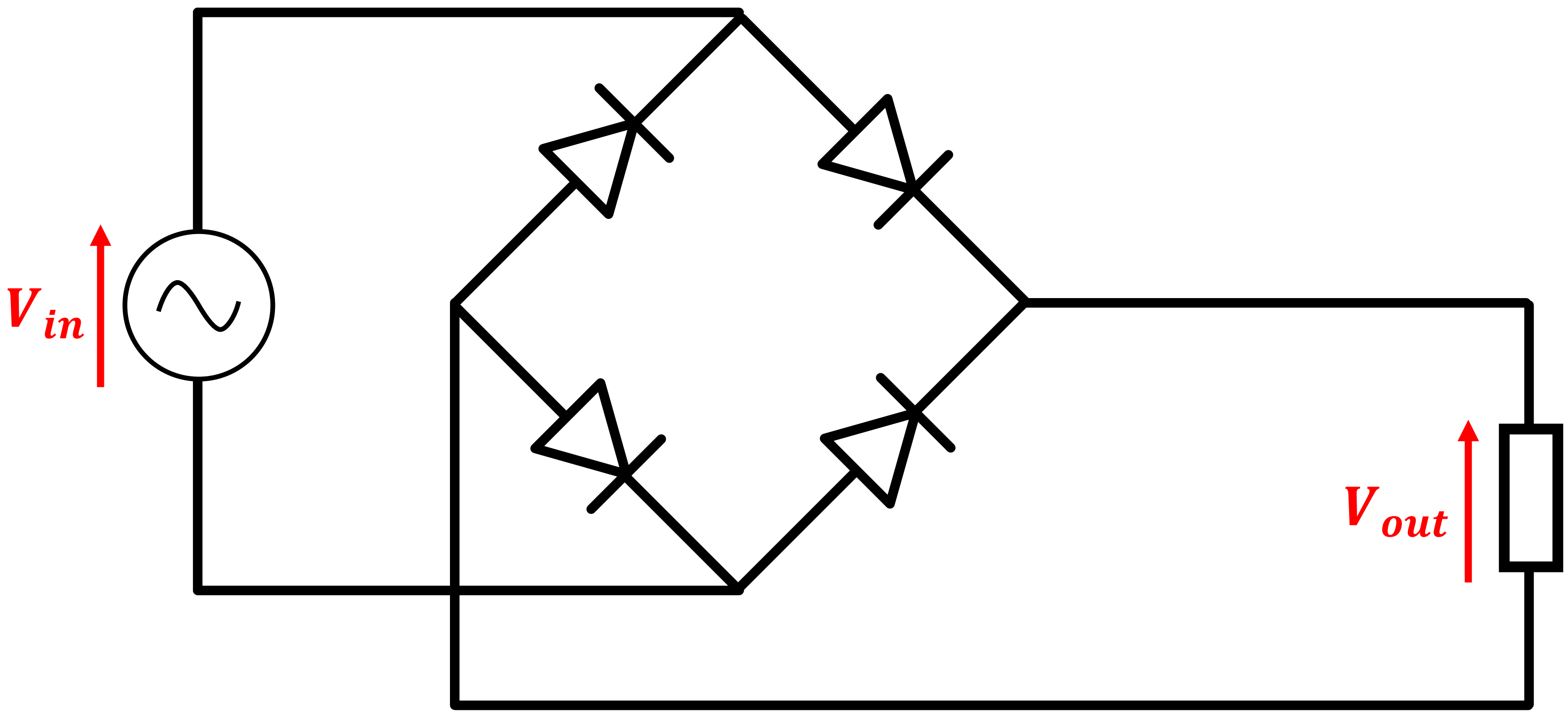


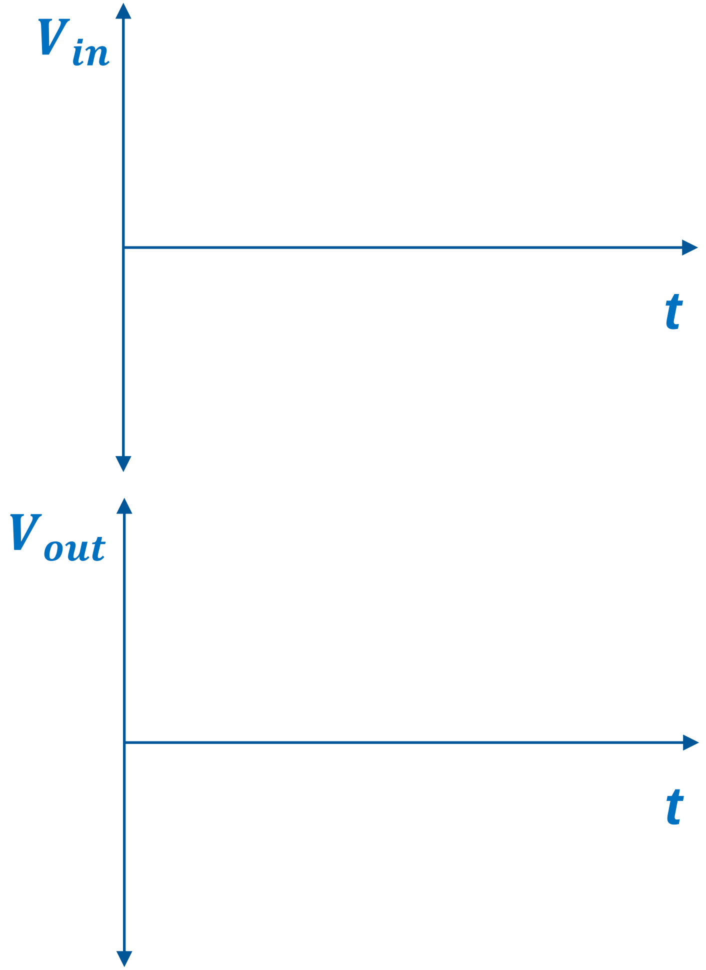
The output is more DC than before (in sense that average voltage is not zero any more) but it still is wasteful!

It is also like turning your laptop charger on/off 50 times a second!

H-Bridge

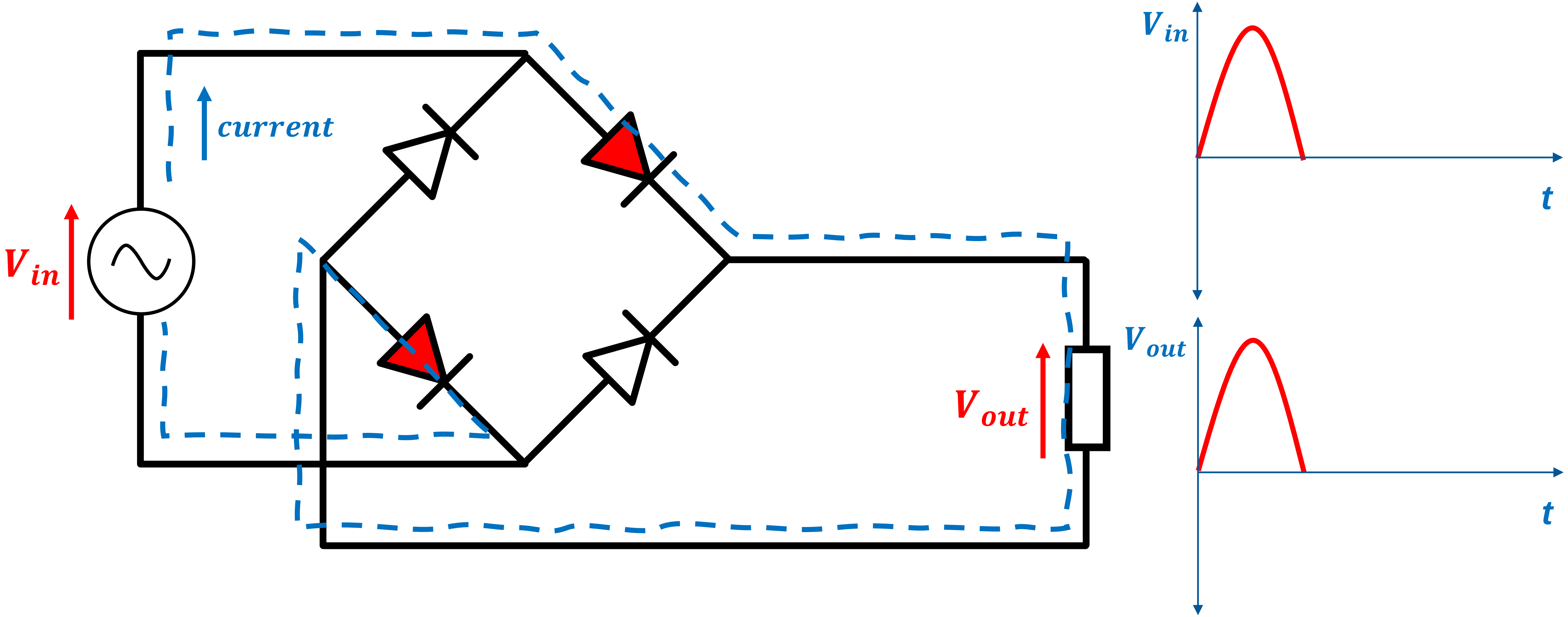
This allows inversion of the negative cycle to take full use of the AC waveform – H-Bridge





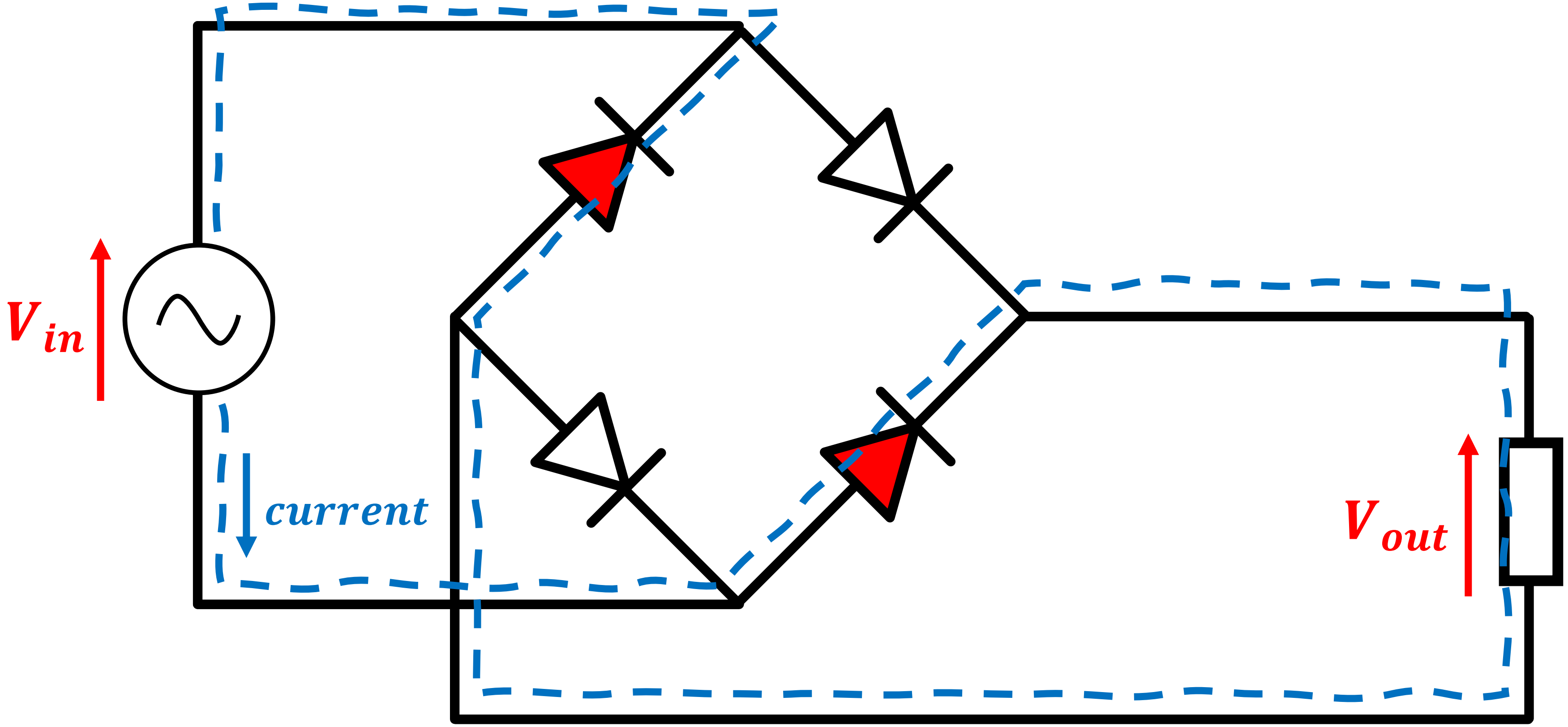
H-Bridge

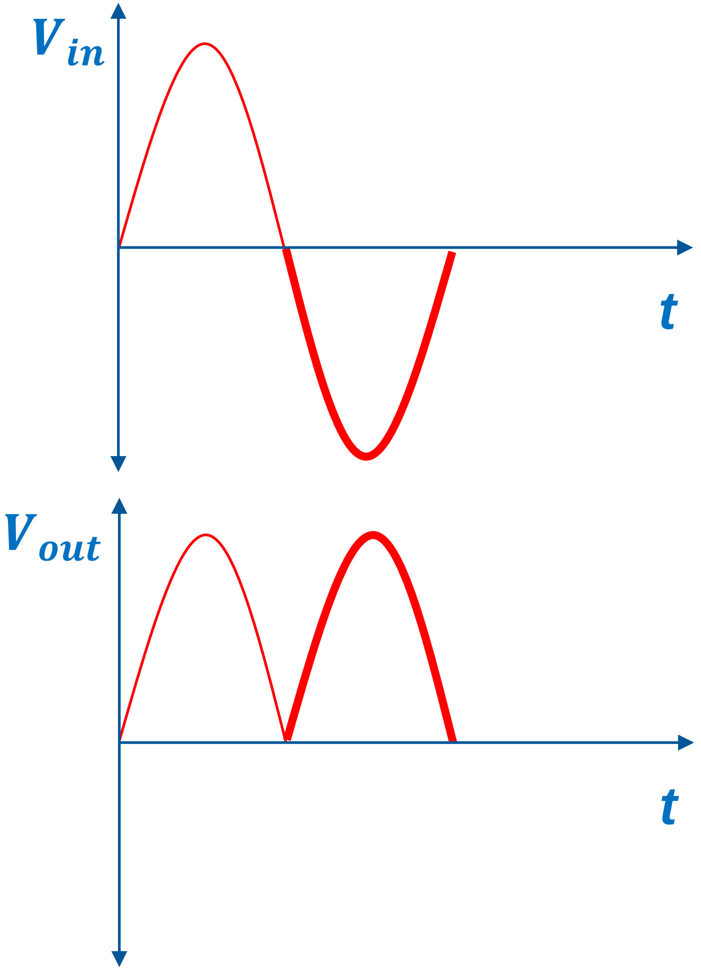
Red diodes active (forward biased), white ones are inactive (reverse biased)



H-Bridge

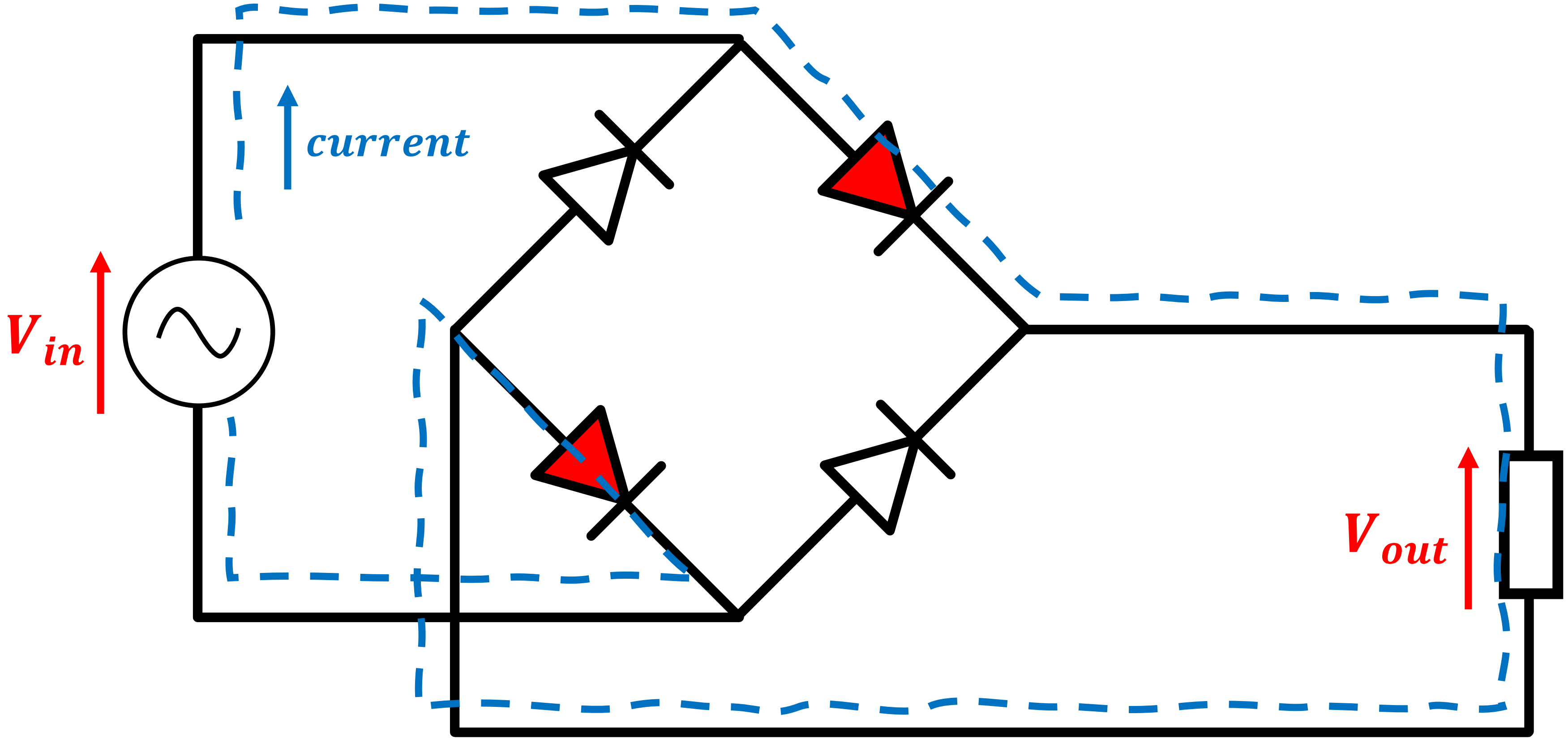
Red diodes active (forward biased), white ones are inactive (reverse biased)

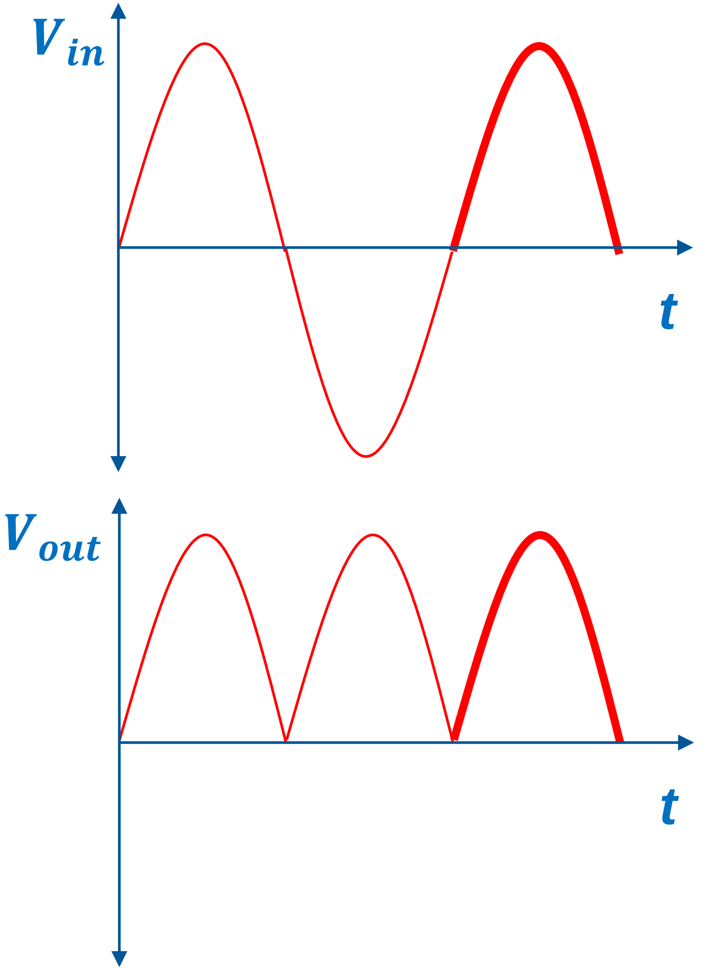




H-Bridge

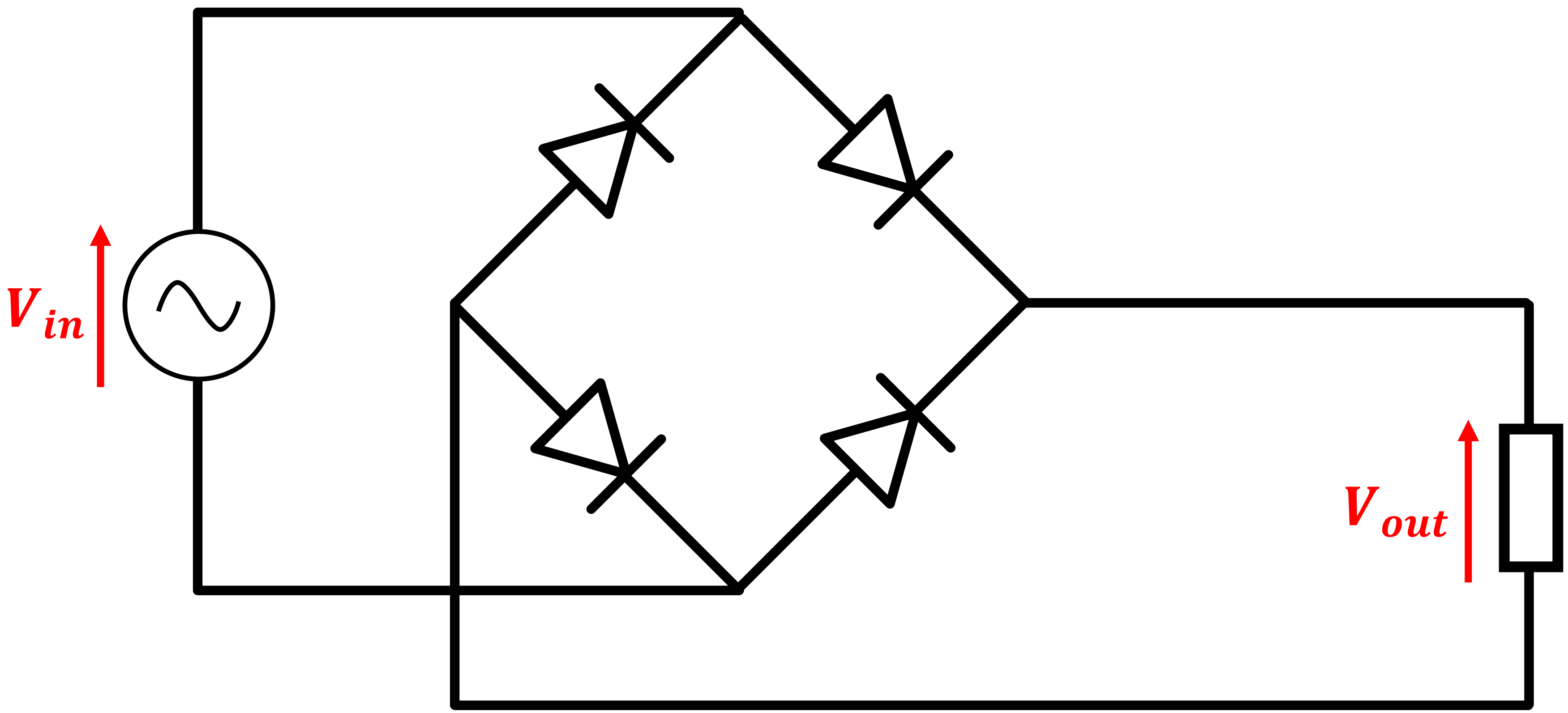
Red diodes active (forward biased), white ones are inactive (reverse biased)

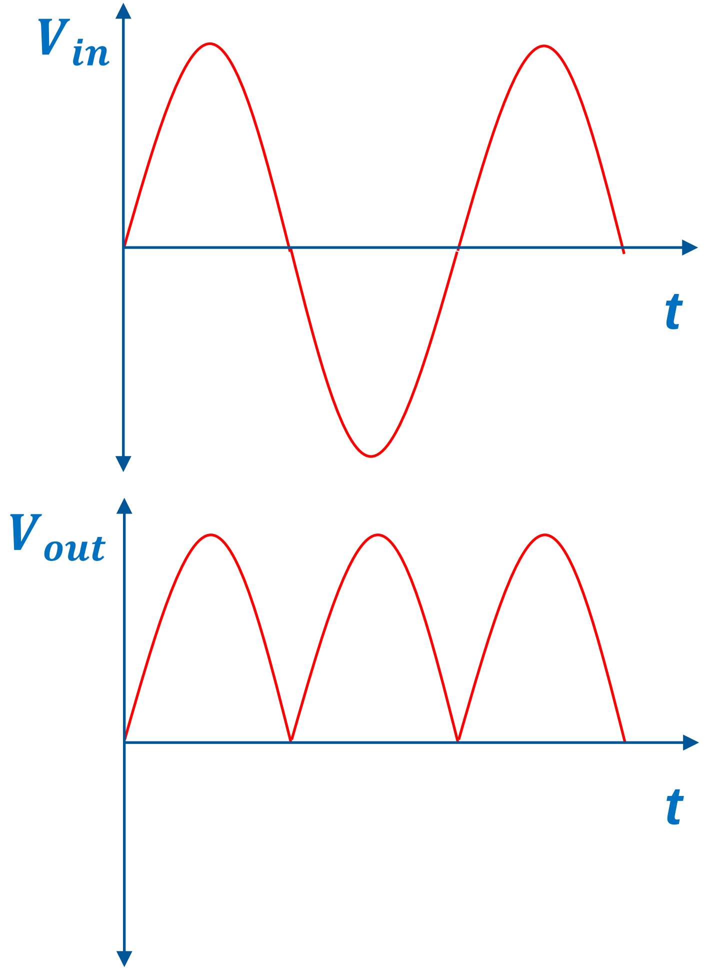




H-Bridge

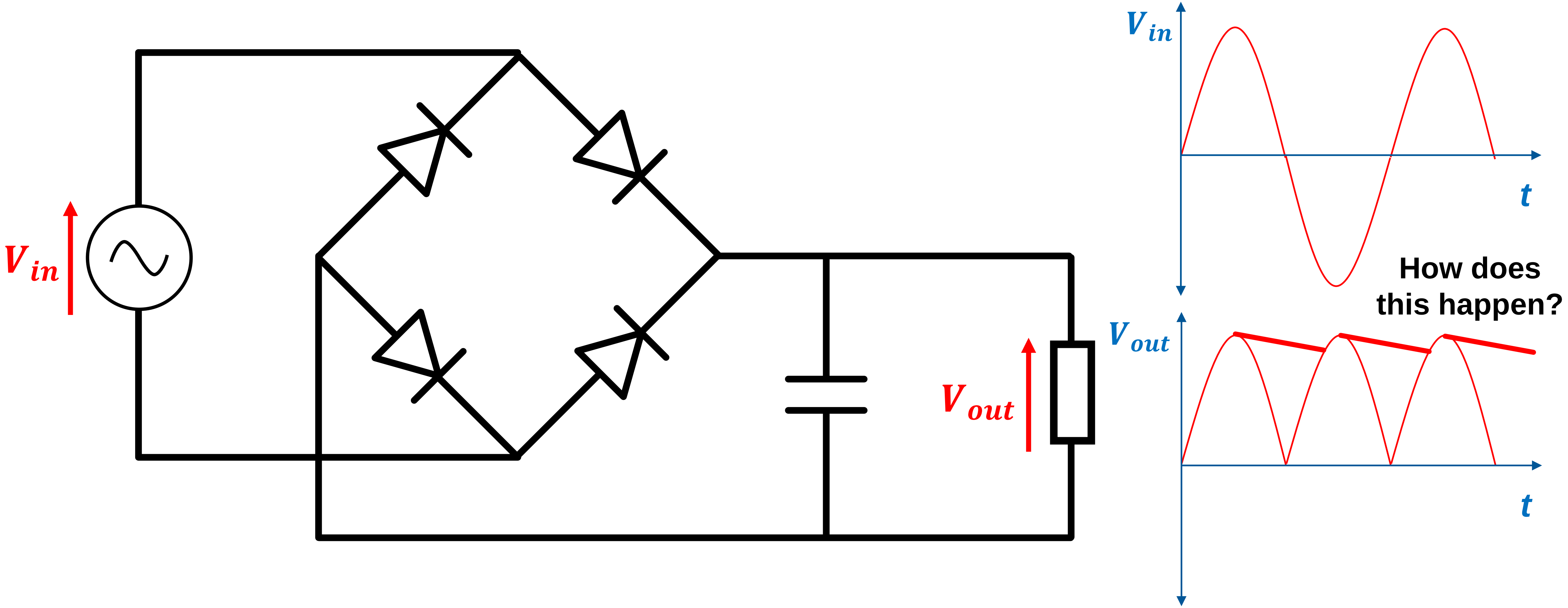
Output voltage is still not a clean DC – they are positive ripples, ripples nonetheless – we need to stabilise the voltage!





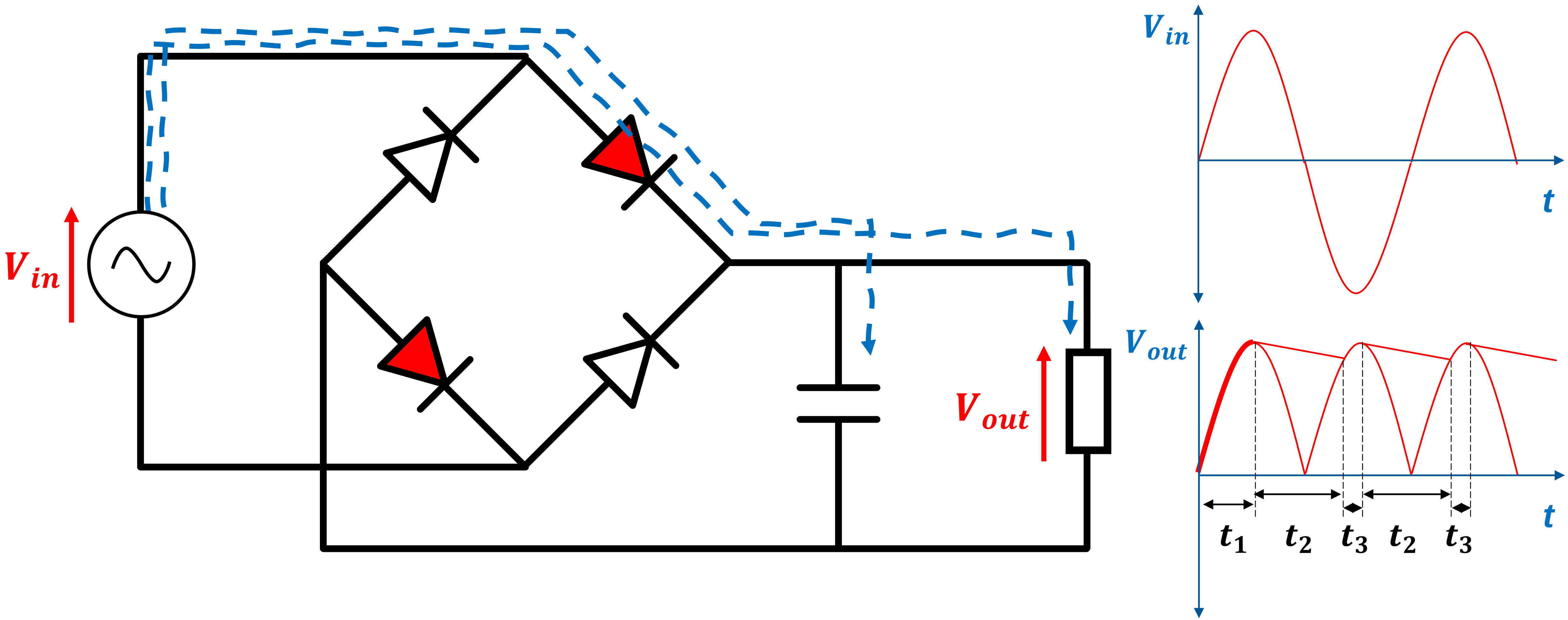
H-Bridge

Capacitors prevent sudden change in voltage (remember?) – we can place an adequately sized capacitor at the output stage



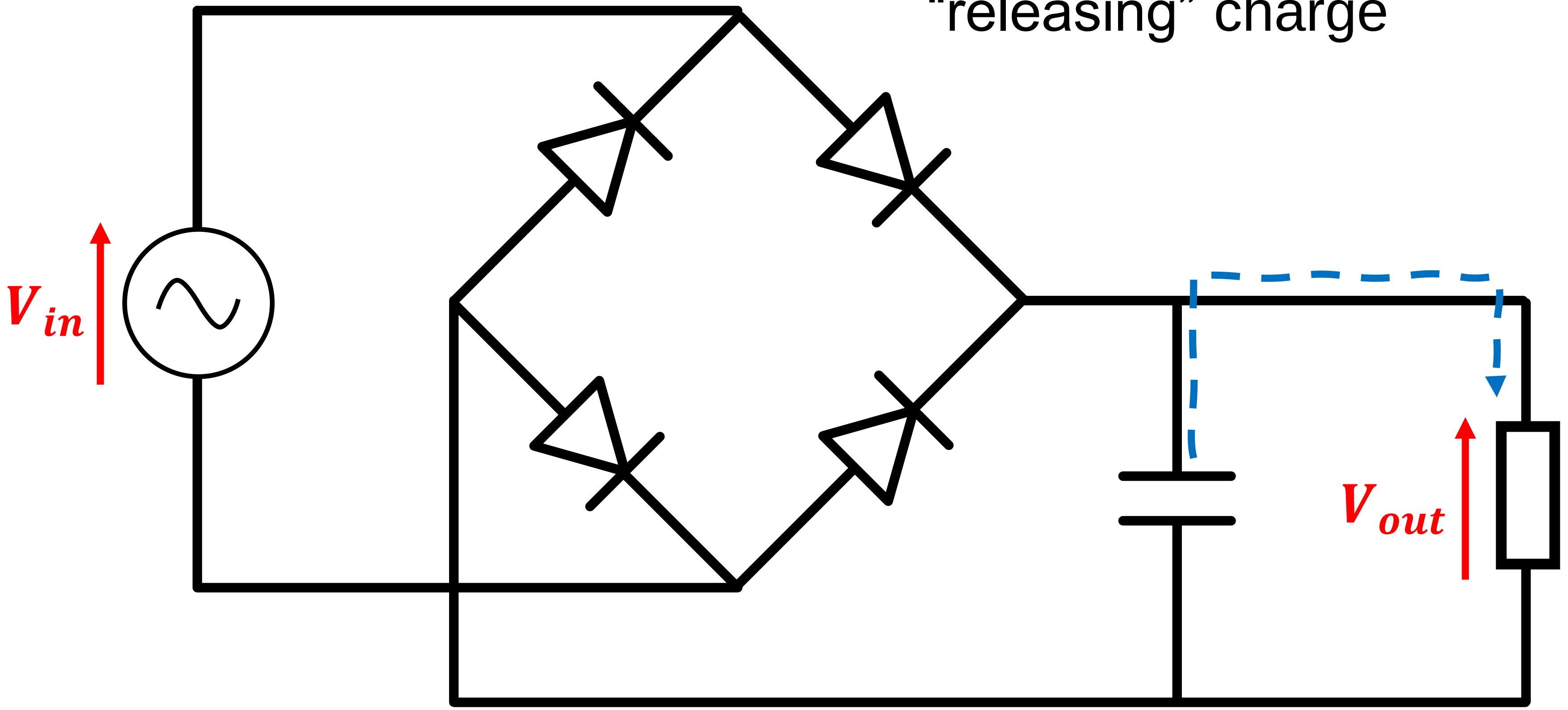
H-Bridge

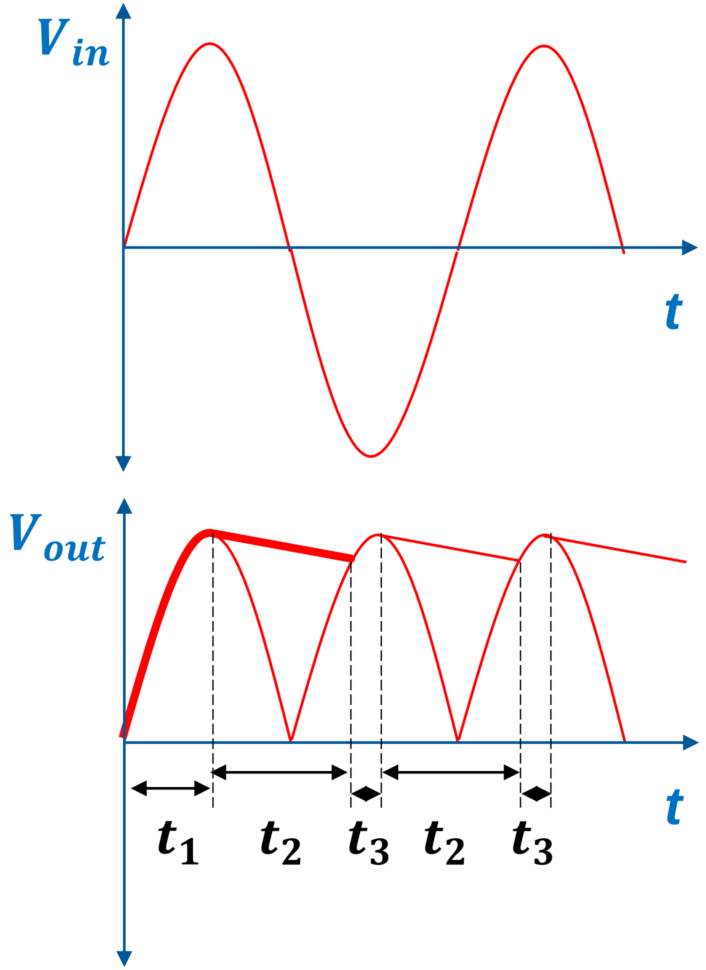
- t_1 Capacitor is charged



H-Bridge

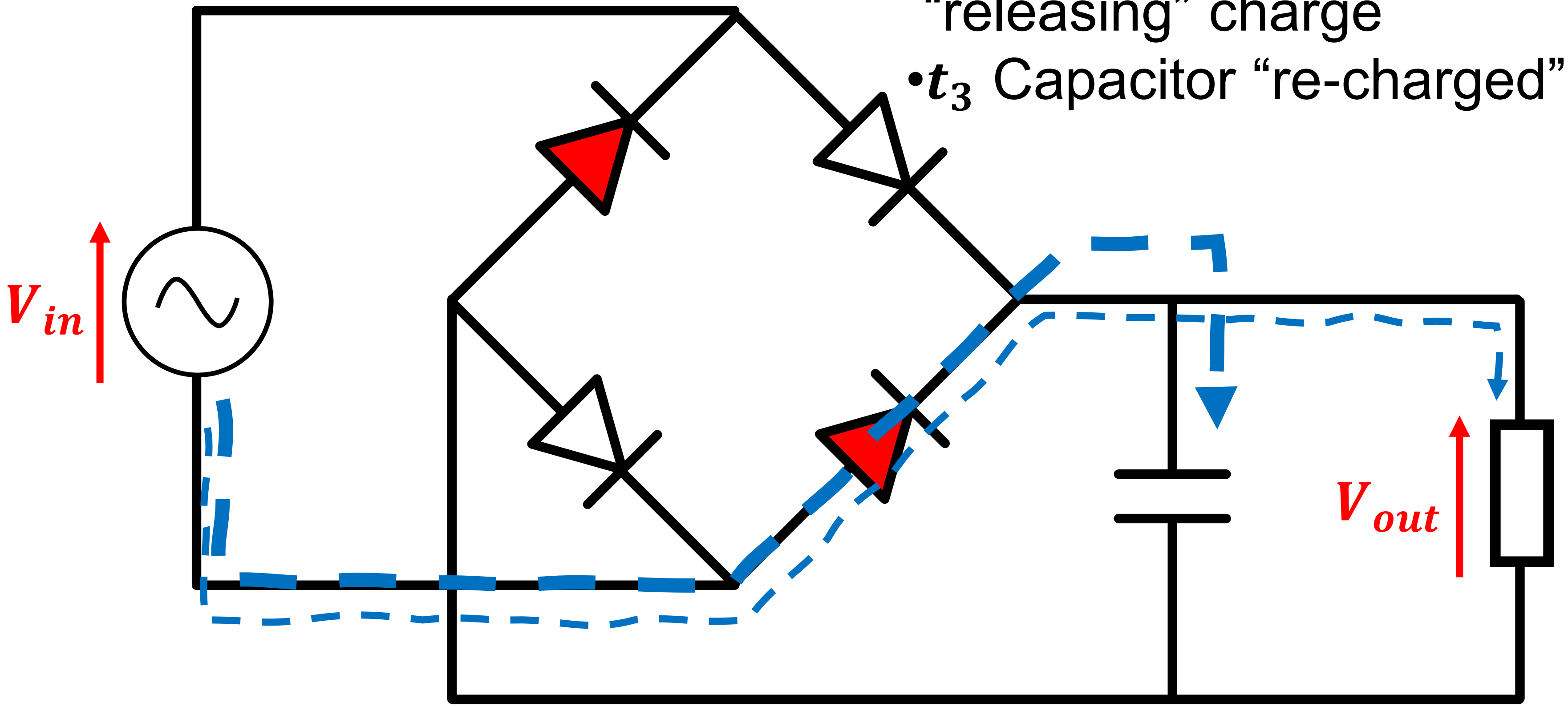
- t_1 Capacitor is charged
- t_2 Capacitor tries to keep the voltage constant by “releasing” charge

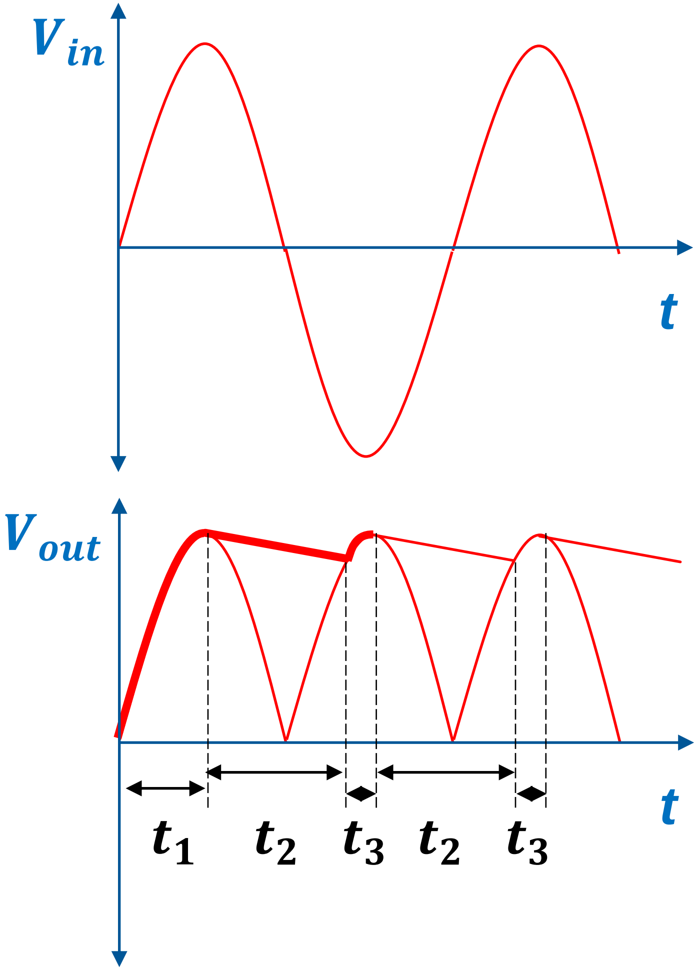




H-Bridge

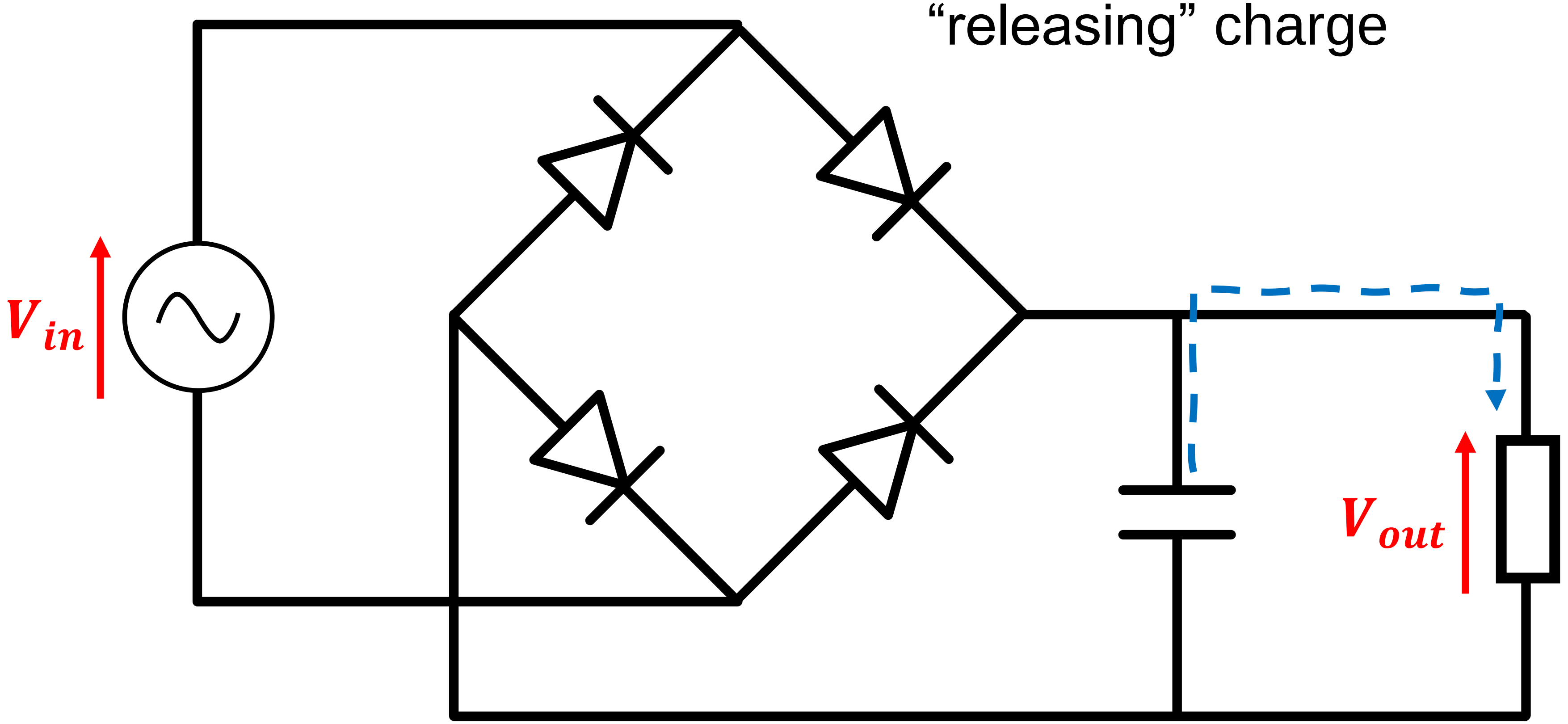
- t_1 Capacitor is charged
- t_2 Capacitor tries to keep the voltage constant by "releasing" charge
- t_3 Capacitor "re-charged"

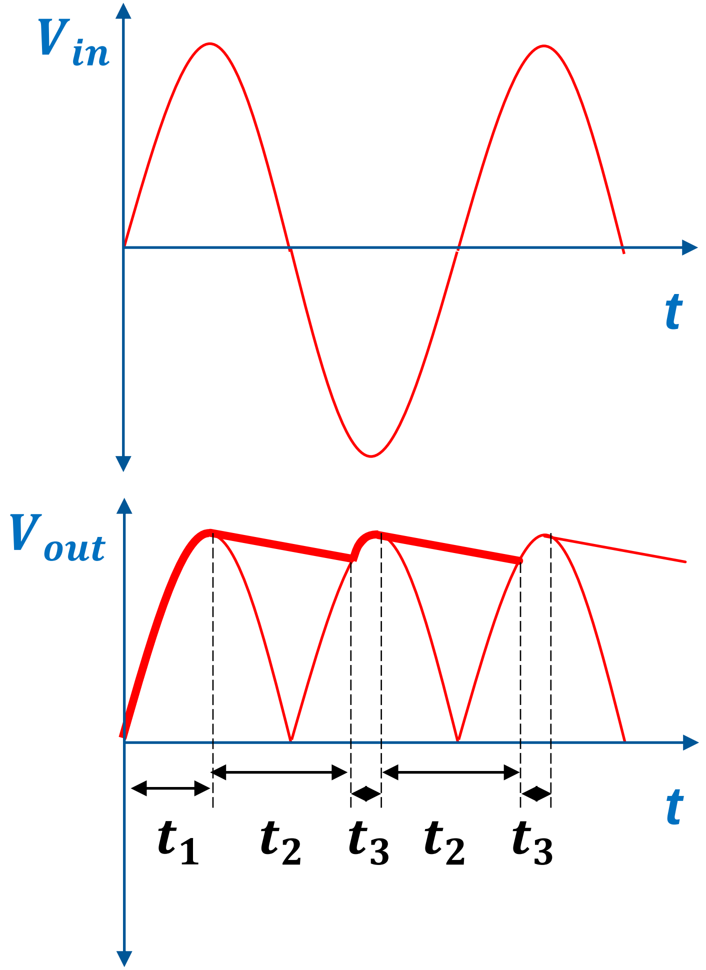




H-Bridge

- t_1 Capacitor is charged
- t_2 Capacitor tries to keep the voltage constant by "releasing" charge





H-Bridge

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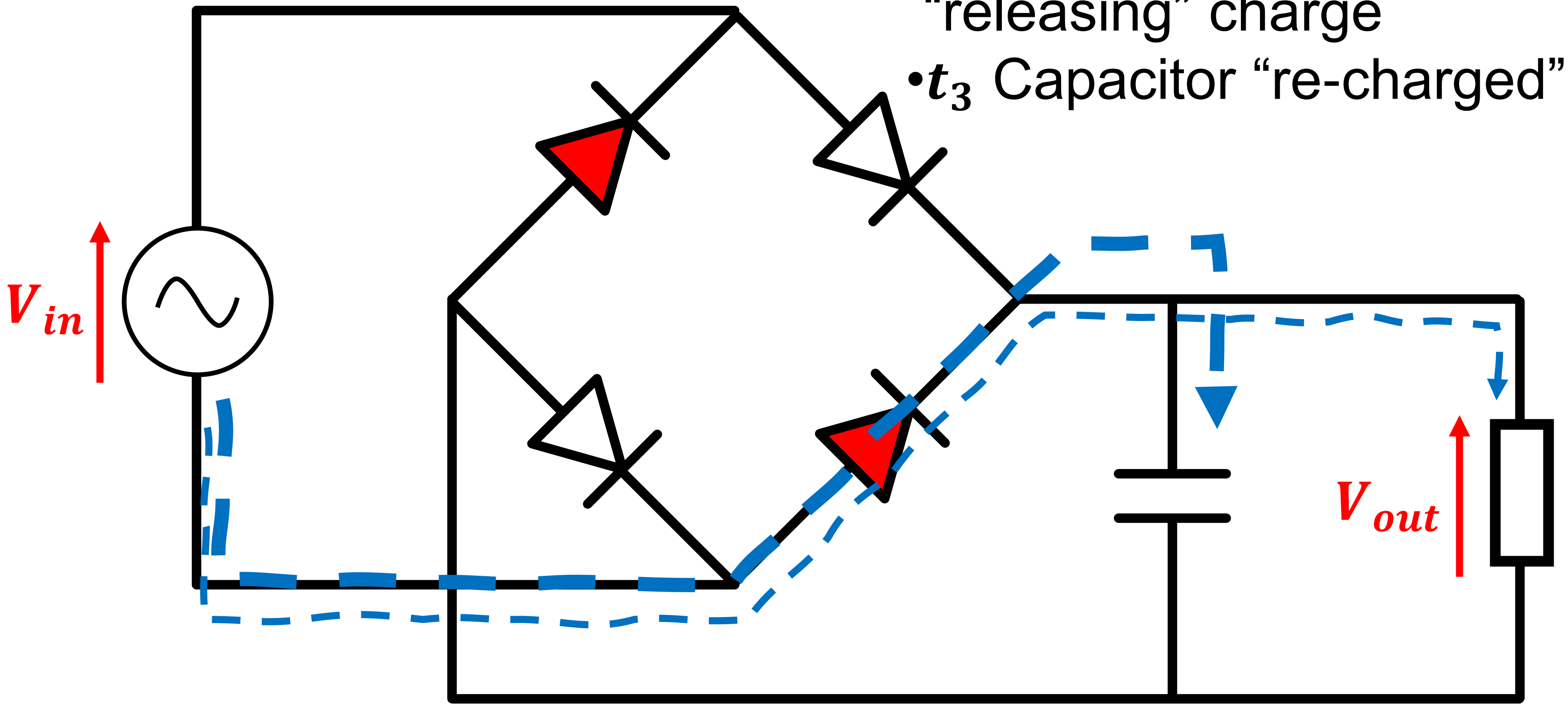

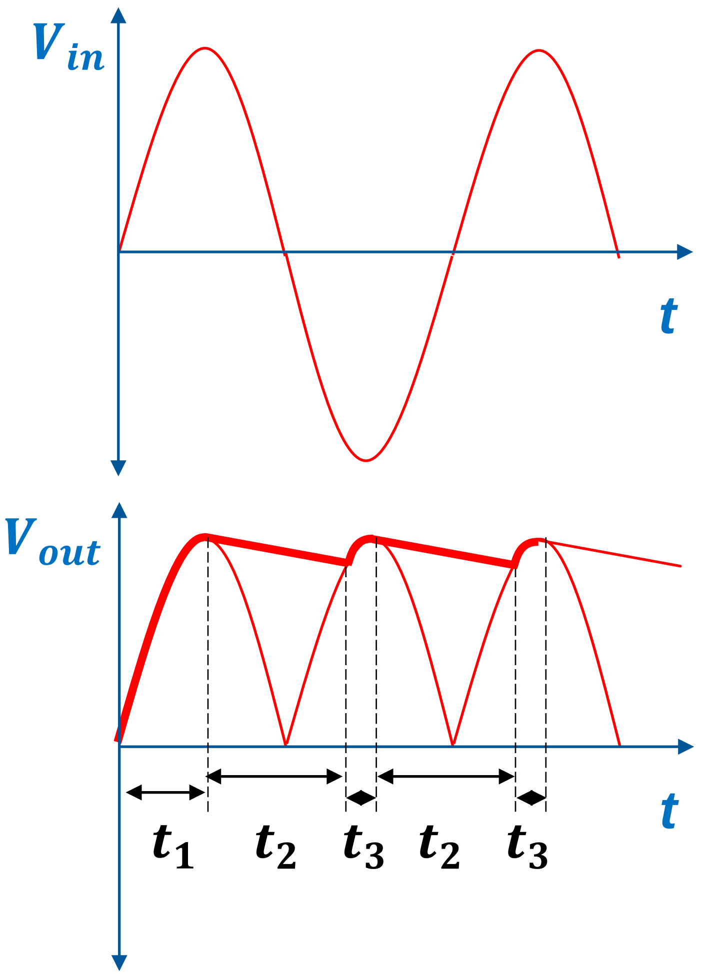

H-Bridge

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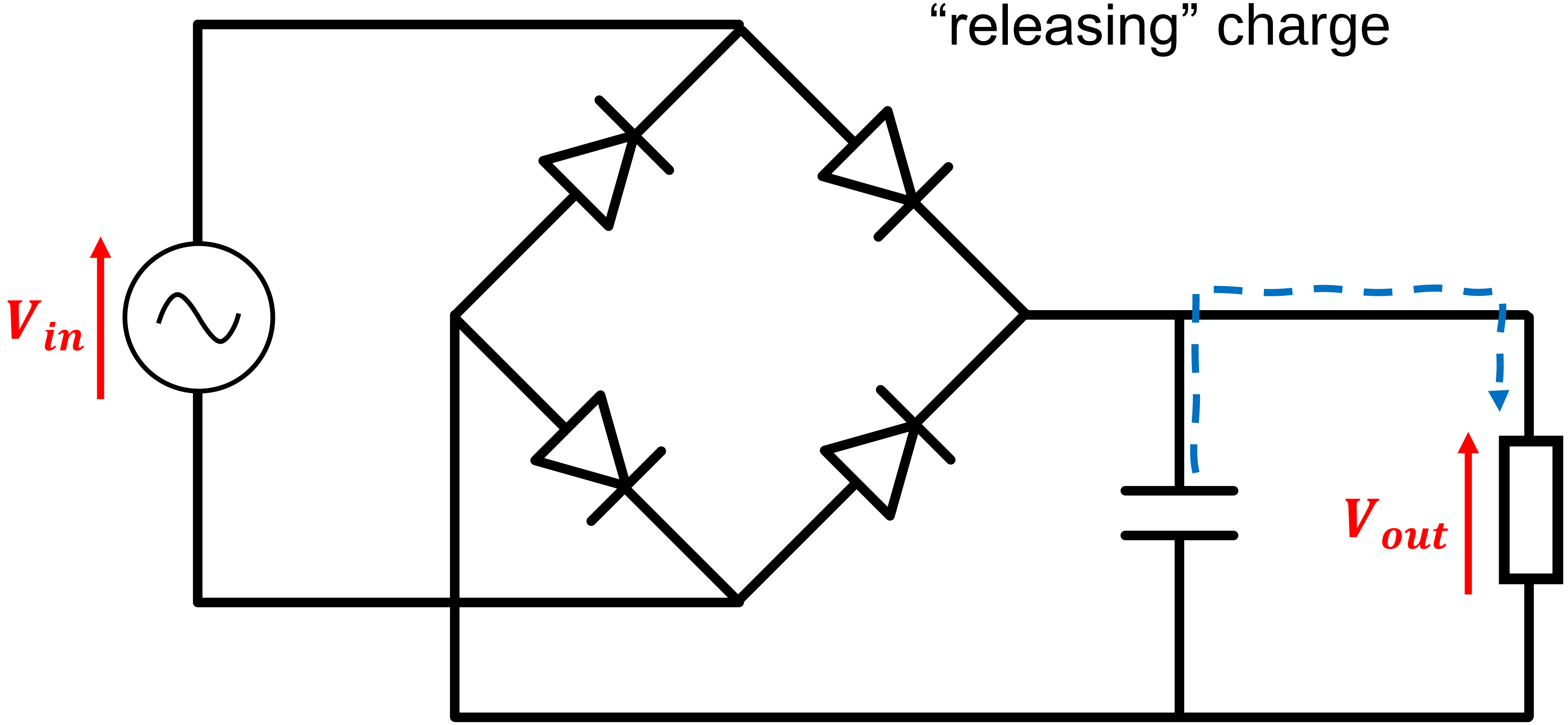

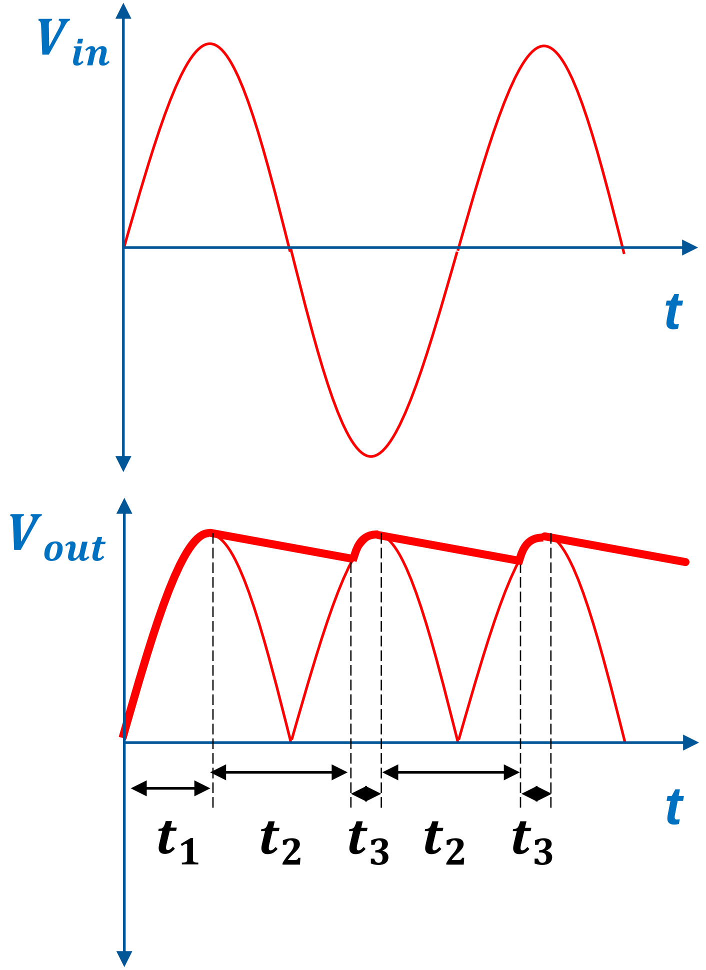

Summary

- **Sustainability Development Goals @UoN**
- Transformers
  - **Electromagnetic induction**
  - Analogy to **gears**
  - **Referred impedance**
- **Diodes**
  - AC to DC – Rectification
  - DC Ripple on Rectifier Output

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Attendance

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