METABOLISM AND THERMOREGULATION

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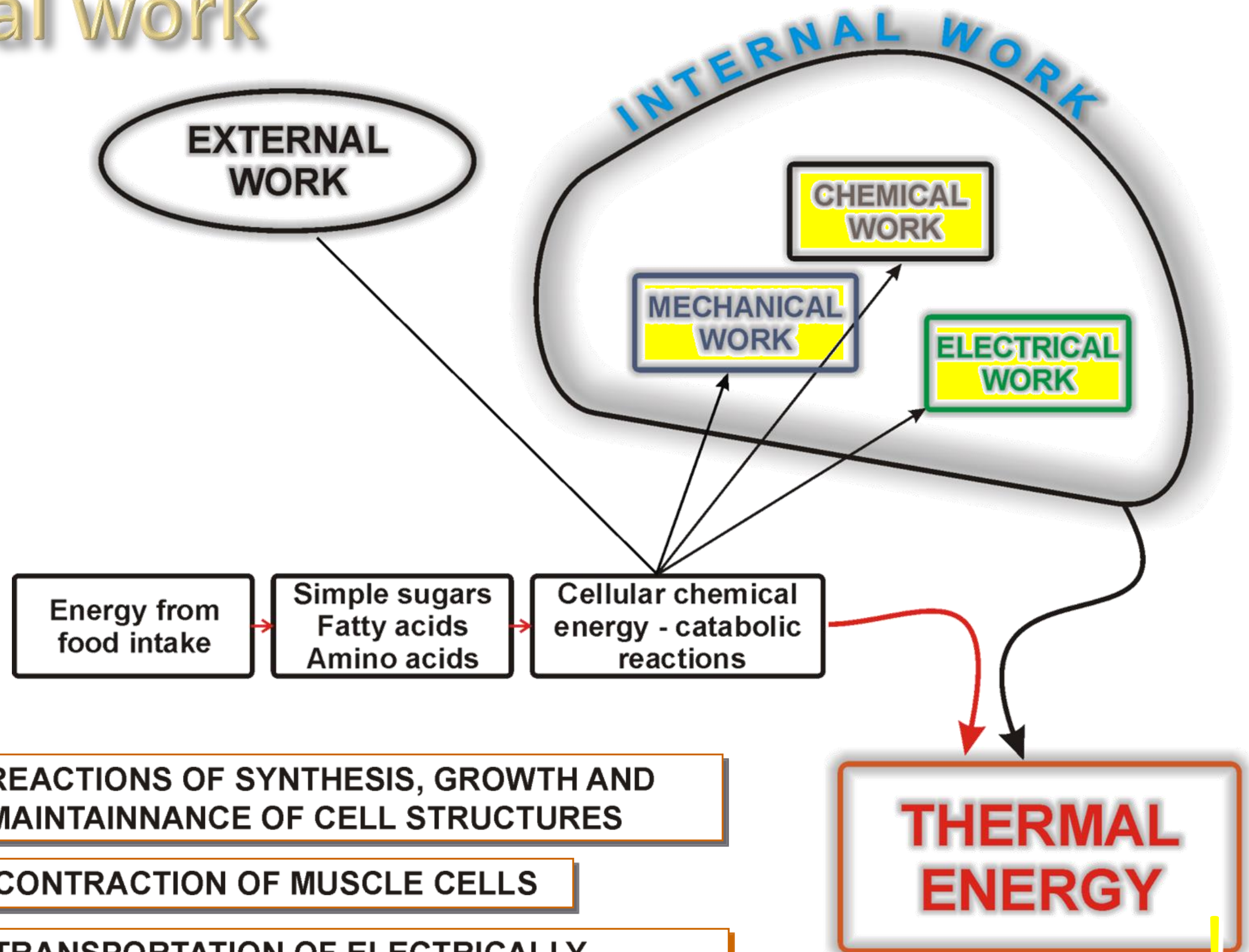
Biological work



CHEMICAL WORK - REACTIONS OF SYNTHESIS, GROWTH AND MAINTAINNANCE OF CELL STRUCTURES

MECHANICAL WORK - CONTRACTION OF MUSCLE CELLS

ELECTRICAL WORK - TRANSPORTATION OF ELECTRICALLY CHARGED MOLECULES UPHILL AN ELECTRIC FIELD GRADIENT

CHEMICAL WORK:

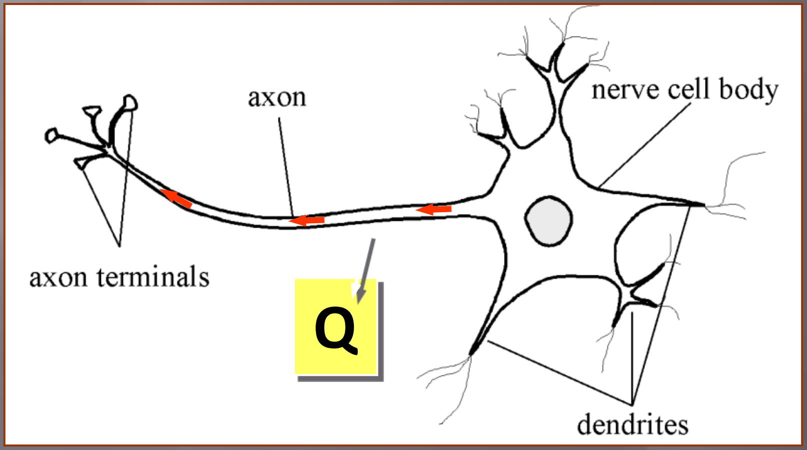
Secretion of hydrochloric acid (HCl) by the stomach and sodium bicarbonate ($NaHCO_3$) by the pancreas.

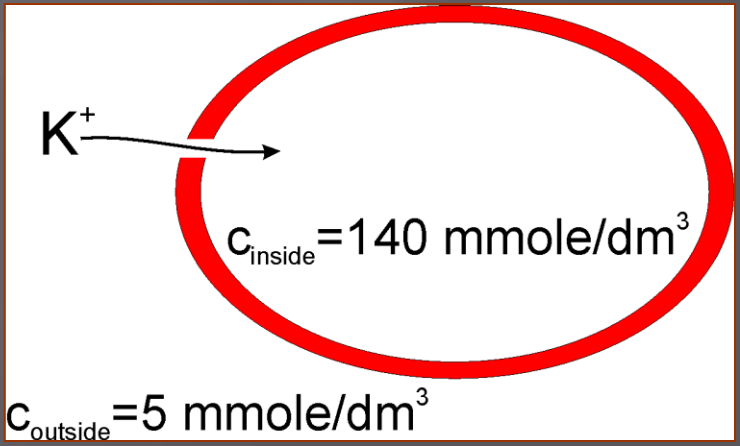
Exo-thermal reaction of H^+ with HCO_3 group in the small intestine.

Q

ELECTRICAL WORK:

All active cells accumulate certain ions against concentration gradient: they accumulate electric energy in electric field which exists across cell membranes.





METABOLIC RATE

The total energy expenditure of the body per unit time

$$\frac{\text{kcalories}}{\text{day}} = \text{Cal} \quad \text{or} \quad \text{Watt}$$

$$(E_{A\text{-}B} + O_2) - (E_{A1} + E_{B1}) = \text{LIBERATED ENERGY}$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 2844\ \text{kJ}$$

- Energy equivalent of oxygen: $\dfrac{\text{energy produced}}{\text{volume of oxygen consumed}}$

- Respiratory quotient $RQ = \dfrac{V_{CO_2}}{V_{O_2}}$

Metabolic values for carbohydrates, fats and proteins

	carbohydrates	fats	proteins
Heat of combustion, kJ/gram	17	39	18
ENERGY EQUIVALENT OF OXYGEN ***w***, kJ per dm^3 O_2	21.2	19.8	18.8
Litres (dm^3) of O_2 consumed per one gram	0.75	2.03	0.97
Litres (dm^3) of CO_2 produced per one gram	0.75	1.43	0.78
RESPIRATORY QUOTIENT ***RQ***	1	0.70	0.80

The average energy equivalent of oxygen *w* for these three sources is 20 kJ per dm^3 O_2.

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + \mathbf{2844\ kJ}$$

180g(1mole) 134.4 l 134.4 l 108 grams heat

$$w = \frac{2844\ \text{kJ}}{134.4\ \text{dm}^3} = 21.2\frac{\text{kJ}}{\text{dm}^3}$$

$$RQ_{carbohydrates} = \frac{134.4\text{dm}^3\ CO_2}{134.4\text{dm}^3\ O_2} = 1$$

MEASUREMENTS OF METABOLIC RATE

METABOLIC RATE = RATE OF OXYGEN CONSUMPTION × ENERGY EQUIVALENT OF OXYGEN!

$$P = \left(\frac{\Delta V}{\Delta t}\right) \times \frac{E}{\Delta V}$$

	carbohydrates	fats	proteins
Energy equivalent of oxygen, kJ per dm^3 O_2 $(E/\Delta t)$	21.2	19.8	18.8

example:

RESPIRATORY CALORIMETRY

EXAMPLE:

How much oxygen you consume in one minute when cycling cycling at 21 km/h?

$$POWER(METABOLIC\ RATE) = RATE\ OF\ OXYGEN\ CONSUMPTION \times ENERGY\ EQUIVALENT\ OF\ OXYGEN$$

$$RATE\ OF\ OXYGEN\ CONSUMPTION = \frac{POWER\ (METABOLIC\ RATE)}{ENERGY\ EQUIVALENT\ OF\ OXYGEN}$$

Energy equivalent of oxygen (standard average) = 20.1 kJ/dm^3

$$S = \frac{\sqrt{mh}}{6}$$

m = 70 kg, h=1,7m

→ S = 1.8m^2

$$P = 394 \frac{\mathrm{W}}{\mathrm{m}^2} \times 1.8 = 710\ \mathrm{W}$$

$$\frac{710\ \mathrm{W}}{20100\ \frac{J}{dm^3}} = 0.035 \frac{\mathrm{dm}^3}{\mathrm{s}}$$

$$\sim 2.1 \frac{\mathrm{dm}^3}{\mathrm{min}}$$

		METABOLIC RATE (ENERGY PRODUCTION)	
	ACTIVITY	kcal per square meter per hour	Watt per square meter
REST	Basal metabolism (standard men)	**38**	**45**
	laying awake	40	**46**
	Sitting relaxed	50	**58**
MODERATE ACTIVITY	Walking at 5 km/h	135	**157**
	Cycling at 5 km/h	195	**226**
	Swimming breastsroke 1.6 km/h	230	**267**
HEAVY ACTIVITY	Cycling at 21 km/h	340	**394**
	Running 15 km/h	473	**550**
	SHIVERRING !!!	to **250**	to **290**

BASAL METABOLIC RATE

***Basal Metabolic Rate* (*BMR*)**
is the *energy* necessary for maintaining basic physiological activities (for the maintenance of homeostasis) per unit time:

- *cardiac output (blood pressure),*
- *muscle tone*
- *brain activity,*
- *renal output,*
- *respiratory function,*
- *ionic gradient restoration*
- *maintainance of body temperature*

Conditions for measurements of BMR

Subject must be :
- *awake*
- *fasting (12 hours)*
- *resting horizontally*
- *comfortable (?) temperature*

BMR depends mainly on the physical characteristics:

- body surface area
- body mass *m*

BASAL METABOLIC RATE (BMR)

It is affected by:

1. Age: children > adults.
2. Sex: males > females.
3. Muscular (physical) activity.
4. Body temperature.
5. Pregnancy, lactation, menstruation.
6. Ingested food (specific dynamic effect !).
7. Diseases and infections.
8. Mental activity and emotional stress.

Exchange of heat occurs through outer surface area!

BMR is mainly affected by physical characteristics.

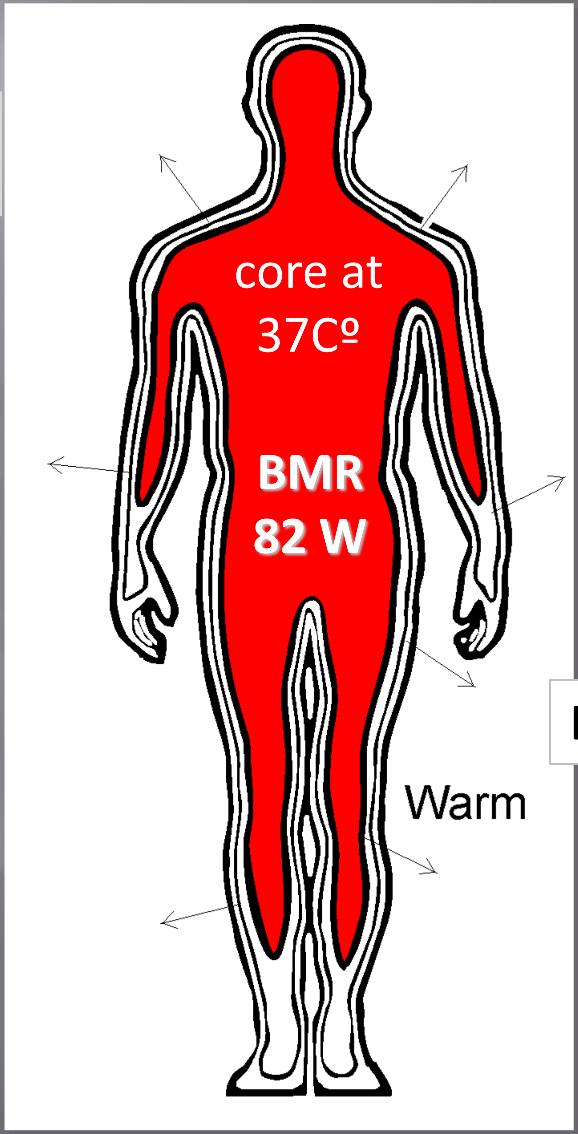
Surface area S correlates with :
- body mass m and
- body shape (height h).

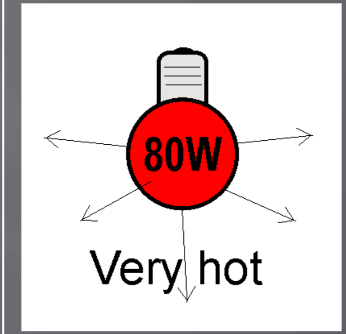
The Mosteller formula:

$$S = \frac{\sqrt{mh}}{6}$$

m =70 kg
h = 1.70 m

S =1.8 m^2





$$BMR = 70 \times m^{0.75} = 1694 \text{ kcal/day}$$

$$BMR = 3.4 \times m^{0.75} = 82 \text{ W}$$

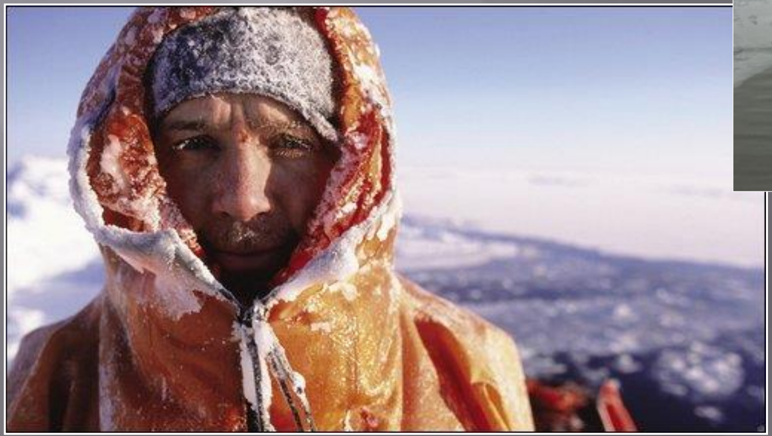
Kleiber, 1961

REGULATION OF BODY TEMPERATURE

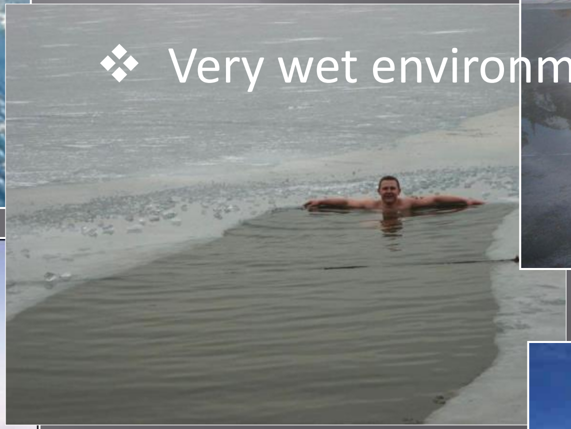
Is it not amazing what a human being is able to withstand?

- Very hot and dry environment

- Very cold environment

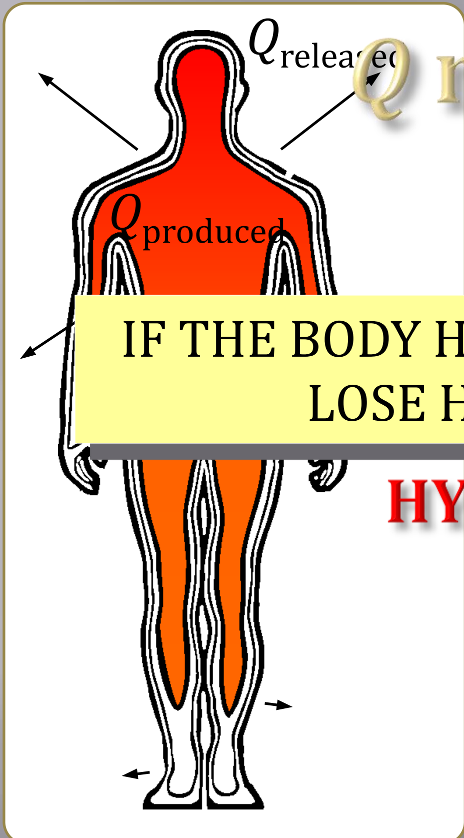


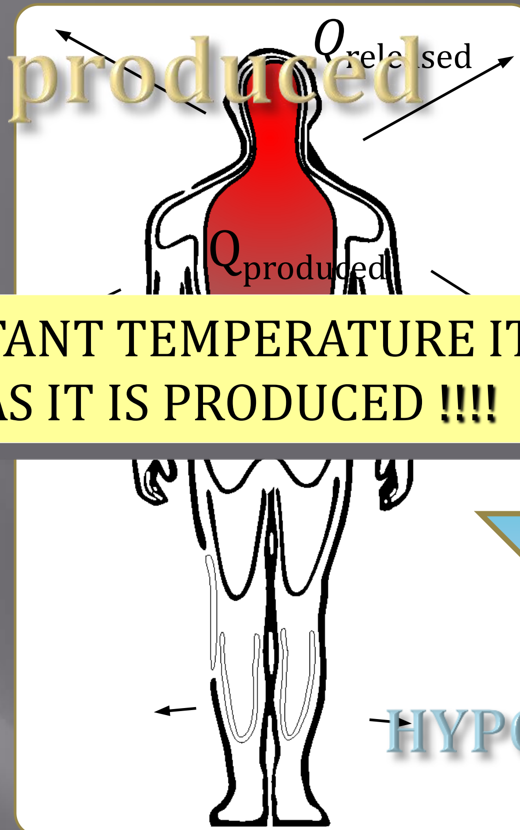
- Very wet environment



- Dry

Q released vs Q produced





IF THE BODY HAS TO MAINTAIN A CONSTANT TEMPERATURE IT MUST LOSE HEAT AT THE SAME RATE AS IT IS PRODUCED !!!!

HYPERTHERMIA

$$\frac{Q_{released}}{\Delta t} < \frac{Q_{produced}}{\Delta t}$$

- When the amount of heat released to the environment is lower than that produced inside the body, the body temperature increases.

HYPOTHERMIA

$$\frac{Q_{released}}{\Delta t} > \frac{Q_{produced}}{\Delta t}$$

When the amount of heat released to the environment is greater than that produced the body temperature decreases.

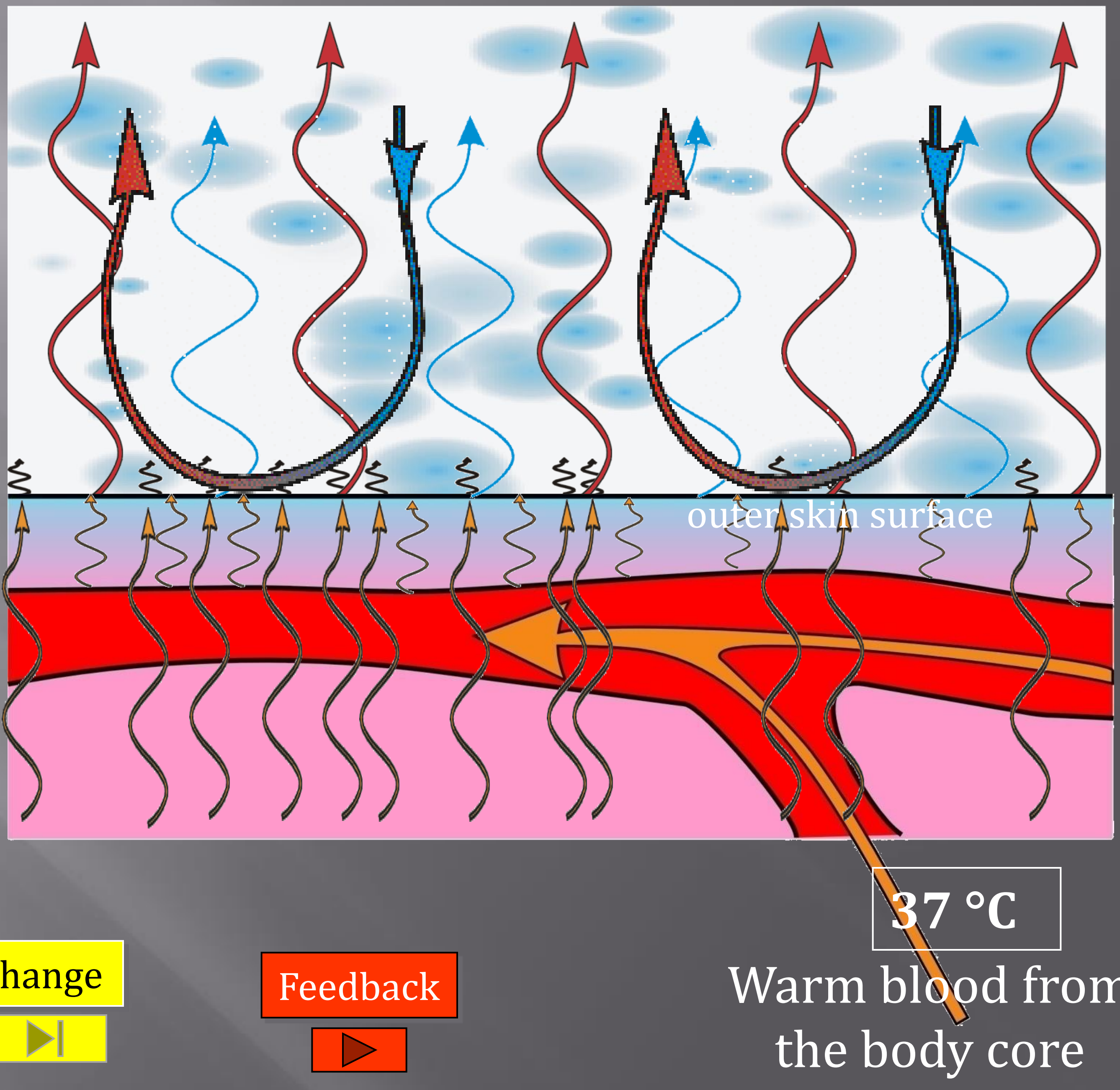
MAIN MECHANISMS OF HEAT EXCHANGE

Conduction

Radiation

Convection

Evaporation (25%)

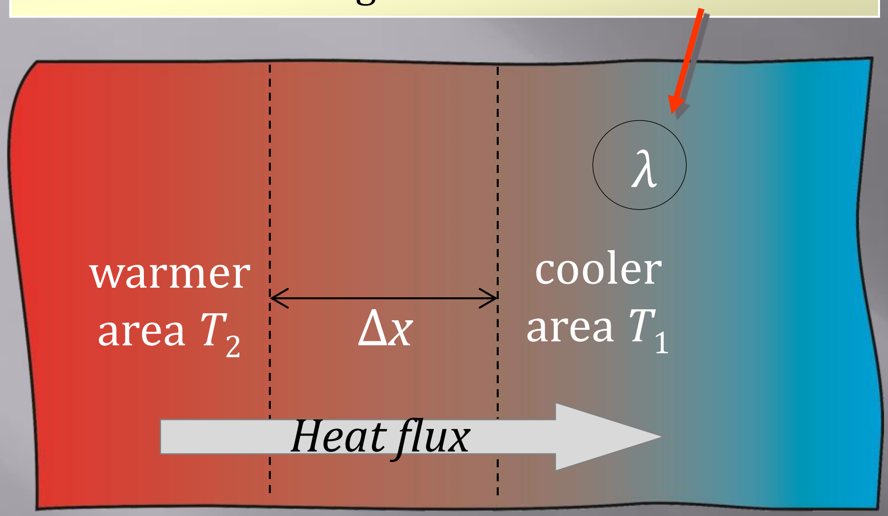


Partition of heat exchange

Feedback

CONDUCTION OF HEAT

λ - the thermal conductivity, characterizes the heat conducting medium



FOURIER LAW

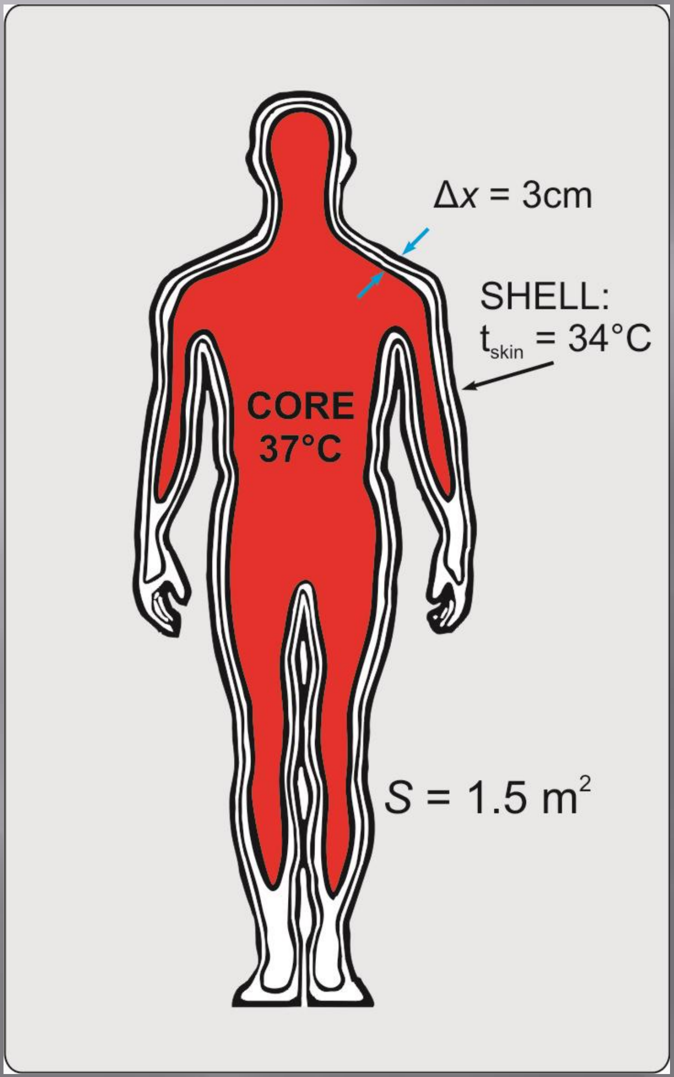
$$\frac{\Delta Q}{S \cdot \Delta t} = -\lambda \frac{\Delta T}{\Delta x}$$

CONDUCTION OF HEAT IS THE TRANSFER OF THERMAL ENERGY FROM ATOM TO ATOM OR MOLECULE TO MOLECULE. IT IS THE TRANSFER OF ENERGY OF RANDOM ATOMIC VIBRATIONS AND MOVING ELECTRONS BY THEIR COLLISIONS, FROM HOTTER TO COOLER PART OF A BODY, ALONG THE TEMPERATURE GRADIENT LINES.

- THE BODY GAINS OR LOSES HEAT BY THE *CONDUCTION* ONLY THROUGHOUT ***DIRECT CONTACT*** WITH WARMER OR COOLER SUBSTANCES!
- THE BETTER THE CONTACT THE HIGHER THE LOSSES.
- THE CONDUCTION OF HEAT PLAYS SIGNIFICANT ROLE IN CARRYING HEAT FROM THE CORE OF HUMAN BODY TO THE SKIN!

THE *HEAT FLUX* $\frac{\Delta Q}{S \cdot \Delta t}$ DEPENDS ON THE MEDIUM (λ), TEMPERATURE GRADIENT $\frac{\Delta T}{\Delta x}$ AND THE SURFACE AREA ***S*** AVAILABLE .

Conduction – example:



Assume that the thickness of the tissue between the interior of the body is 3 cm and that the average area through the which conduction can occur is 1.5 m^2.

Calculate the amount of heat conducted from the core to the shell in unit time (i.e. the power).

Compare it with basal metabolic rate (BMR) equal to 82 W.

$$\frac{\Delta Q}{\Delta t} = -\lambda S \frac{\Delta T}{\Delta x}$$

$$P = -\lambda S \frac{\Delta T}{\Delta x}$$

λ_{tissue} = 0.2 W/mK

P = 0.2 W/mK· 1.5 m^2 · (3K/0.03 m) = 30 W

37% of *BMR*

RADIATION: THE HEAT TRANSFER IN FORM OF THE ELECTROMAGNETIC RADIATION

Radiation is the heat transfer by electromagnetic waves between objects that are NOT IN CONTACT !

THE STEFAN-BOLTZMANN LAW

$$\frac{\Delta Q}{S \cdot \Delta t} = \varepsilon\sigma T^4 \quad \text{or} \quad P = \varepsilon\sigma S T^4$$

P - total power radiated by a body of surface S,
T - temperature of a body (in absolute scale)
σ - Stefan-Boltzmann constant
ε - emissivity of an object ($\varepsilon = 1$ for ideal radiator - black body)

EXAMPLE:

Calculate the amount of heat **radiated** from skin (T_s = 34°C) to the environment (at T_e (20°).

OBJECTS (INCLUDING HUMAN BODY) NOT ONLY RADIATE BUT ALSO ABSORB THE RADIANT (ELECTROMAGNETIC) ENERGY:

$$P_{net} = P_{emitted} - P_{absorbed} = \sigma S(T_1^4 - T_2^4)$$

$$P_{net} = \sigma S(T_1^4 - T_2^4) = 5{,}67 \frac{\mathrm{W}}{\mathrm{m^2K^4}} \times 10^{-8} \times 1.80\ \mathrm{m}^2 \times (307\mathrm{K}^4 - 293\mathrm{K}^4) = 154\ \mathrm{W}$$

Basal metabolic rate for standard man (30 year, 70 kg, 1.80 m^2): 82 W

$\sim 190\%\ of\ BMR$

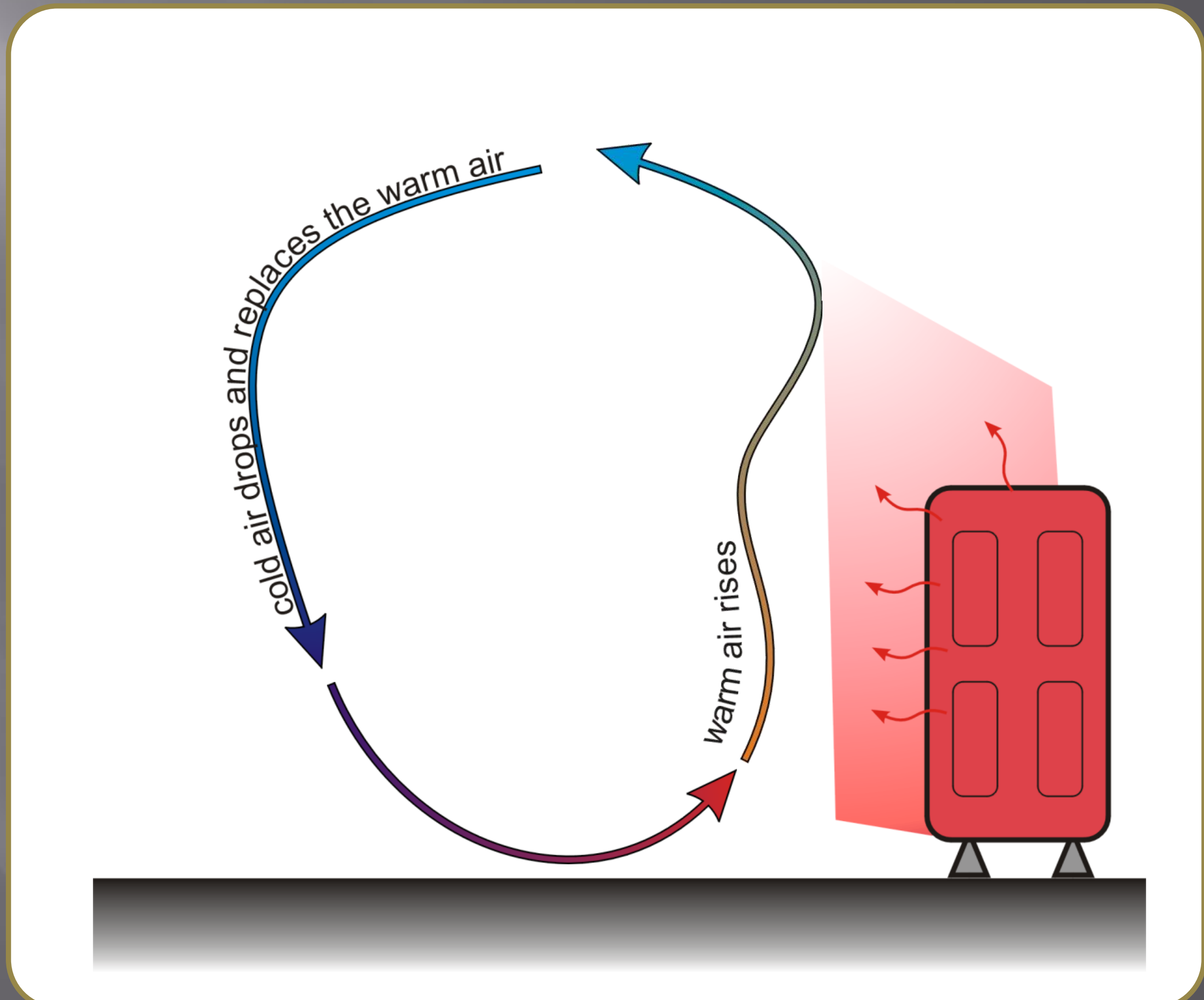
CONVECTION

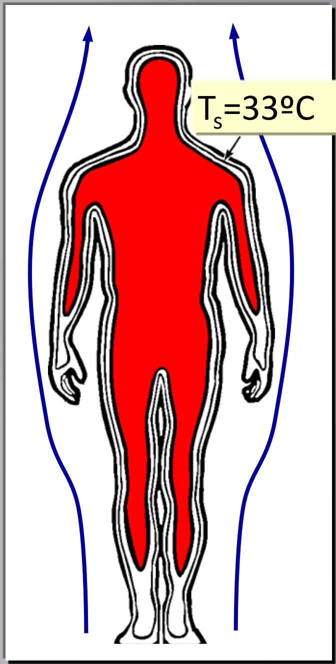
<u>CONVECTION</u> IS THE HEAT TRANSFER BY MASS MOTION OF A FLUID SUCH AS AIR OR WATER WHEN THE HEATED FLUID IS CAUSED TO MOVE AWAY FROM THE SOURCE OF HEAT, CARRYING ENERGY WITH IT.

$$\frac{\Delta Q}{S\Delta t} = K_{conv.}(T_S - T_A)$$

$$P = K_{conv.}S(T_S - T_A)$$

$K_{conv.}$ – a coefficient that depends upon movement of the air ,
S – the effective surface area,
T_S – temperature of the skin,
T_A – the temperature of the convective fluid (air).





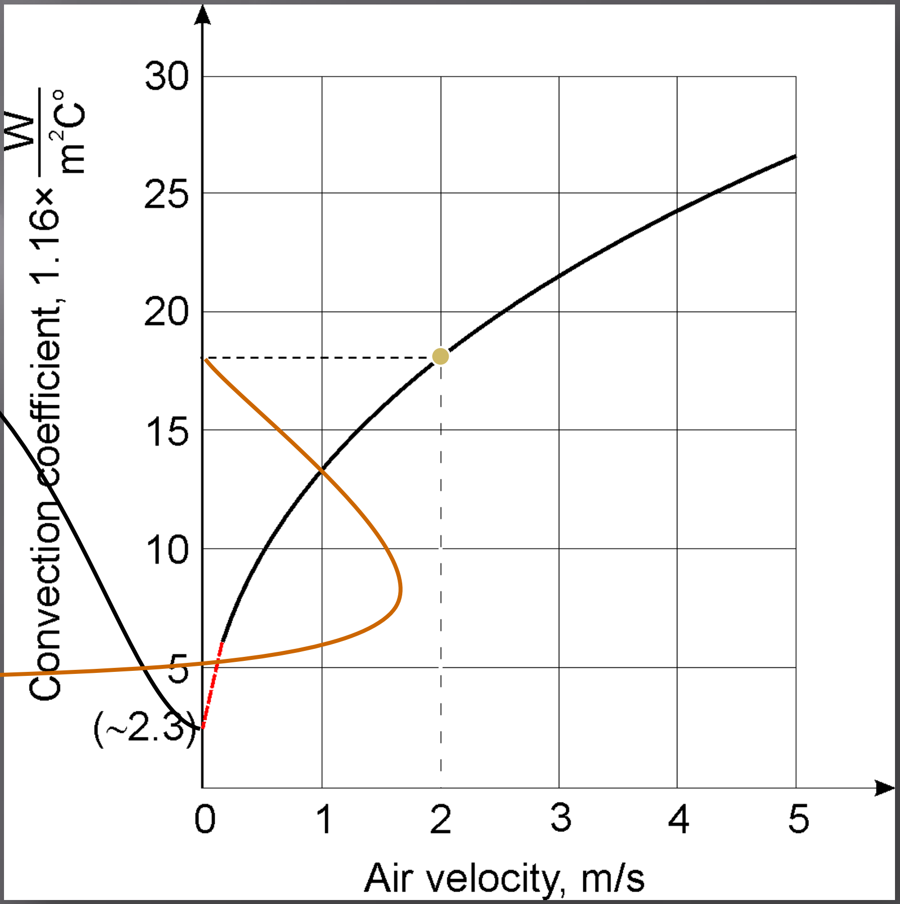
EXAMPLE:

Determine the rate of heat lost due to convection.

$$P = K_{conv.} S(T_S - T_A)$$

Effective surface area S =1 m^2
Air temperature: T_A = 25ºC
Skin temperature: T_S = 33ºC

(*) - THE WIND CHILL FACTOR



1º Resting body, no wind

$$K_{conv.} \approx 2.7 \frac{W}{m^2C^\circ}$$

$$P = 2.7 \frac{W}{m^2C^\circ} \times 1m^2 \times (33C^\circ - 25C^\circ) \approx 22W$$

27%

2º Wind speed: 2 m/s

$$18 \times 1.16 \approx 21 \frac{W}{m^2C^\circ}$$

$$P = 21 \frac{W}{m^2C^\circ} \times 1m^2 \times (33C^\circ - 25C^\circ) \approx 170W$$

207%

EVAPORATION

$$\frac{\Delta Q_{\text{ev.}}}{S\Delta t} = K_{\text{ev.}}(\mathrm{p_S} - p_{\mathrm{E}})$$

$$P = K_{\text{ev.}} S(p_{\mathrm{S}} - p_{\mathrm{E}})$$

p_S – *partial pressure of water vapor at the skin surface,*
p_E – *partial pressure of water vapor in the environment,*
$K_{ev.}$ – *proportionality coefficient.*

MECHANISM:
THERMAL ENERGY IS REQUIRED TO TRANSFORM WATER FROM THE LIQUID TO THE GASEOUS STATE. THUS WHENEVER WATER VAPORIZES FROM THE BODY SURFACE, THE HEAT REQUIRED TO DRIVE THE PROCESS IS CONDUCTED FROM THE SKIN - THEREBY COOLING IT.

EXAMPLE: Calculate the power necessary to evaporate 600 g of water (insensible sweating) in 24 hour:

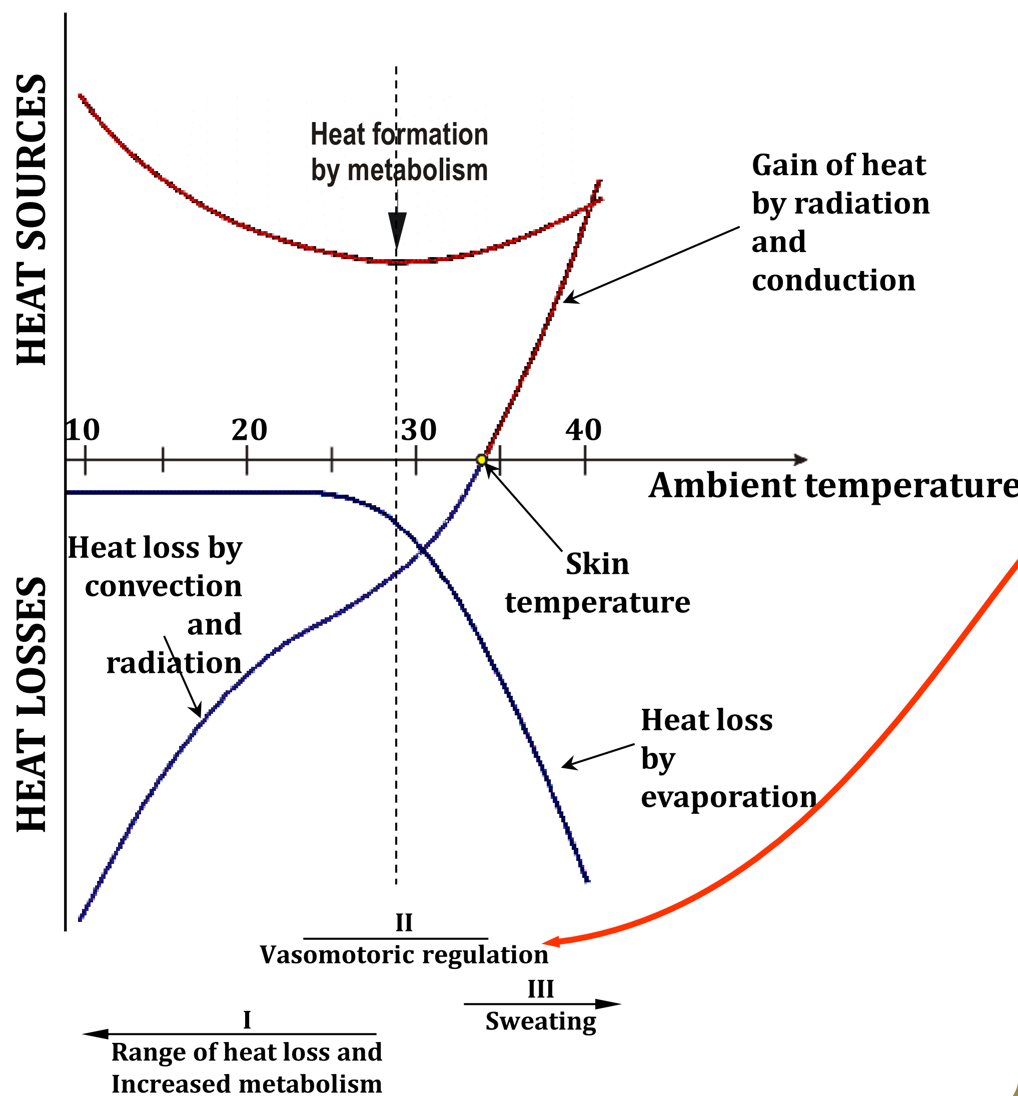
The amount of thermal energy necessary to change 1kg of water into water vapour (heat of vaporization) at skin temperature approximately equals 2.4×10^6 J/kg

$$P = \frac{0{,}600\ \mathrm{kg} \cdot 2.4 \times 106\ \frac{\mathrm{J}}{\mathrm{kg}}}{24\ \mathrm{h} \cdot 3600\ \mathrm{s}} = 17\ \mathrm{W}$$

21% of BMR

EVAPORATION OF WATER FROM THE SKIN AND THE LINING MEMBRANES OF THE RESPIRATORY TRACT IS ONE OF MAJOR PROCESSES FOR LOSS OF BODY HEAT AT HIGH TEMPERATURES!

PARTITION OF HEAT EXCHANGE



VASCULAR RESISTANCE

$$R_v = \frac{8\eta l}{\pi r^4}$$

Feedback

45 44 43	Nerve malfunction and brain damage	Breakdown in heat-regulating system – tthermoregulation inactive
42		Thermoregulation substantially disturbed
41 40 39 38	Hard exercise, hard work, fever, emotion	Effective thermoregulation 35-41°C
37 36 35	Usual range of normal	
34 33 32 31		**HYPOTHERMIA** Thermoregulation substantially disturbed
30 29 28		Thermoregulation Inactive

(From: Human Physiology, Vander, Sherman, Luciano)

Affected by:
- diurnal cycle 5:00 am - *minimum,* 14:00-16:00 *maximum*
- menstrual cycle

ANALYSIS OF DATA

Naked person sitting still

Comfort temperature	Relative air speed	Heat transferred from person to surroundings				
		Convection	Radiation	Latent vapor (insensible sweating)		Total
(°C)	(m/s)	(watt)	(watt)	(g/h)	(watt)	(watt)
28.8	< 0.1	36 (34%)	39 (40%)	40	27 (26%)	102
30.1	0.3	47	29	40	27	102
30.7	0.5	51	24	40	27	102
31.4	1.0	57(56%)	19 (18%)	40	27 (26%)	102

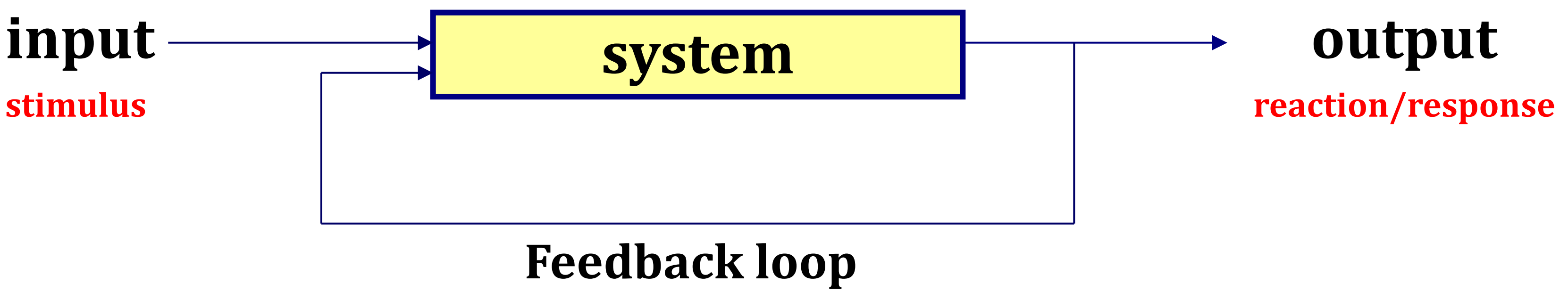
http://www.engineeringtoolbox.com/metabolism-clothing-activity-d_117.html

Factors affecting metabolic rate

	ACTIVITY	Watt per square meter	Kilocalories per square meter per hour
REST	sleeping	41	35
	laying awake	46	40
	Sitting upright	58	50
MODERATE ACTIVITY	Walking 5 km/h	163	140
	housework	163	140
	bicycling	290	250
HEAVY ACTIVITY	Skiing	580	500
	running	700	600
	SHIVERRING !!!	to 290	to 250

Feedback

A characteristic of a control system in which the output response influences the input to the control system.



Negative feedback:

is a type of feedback during which a system responds so as to reverse the direction of change.

Since this process tends to keep things constant, **it is stabilizing** and attempts to maintain **homeostasis**.

Negative feedback loop