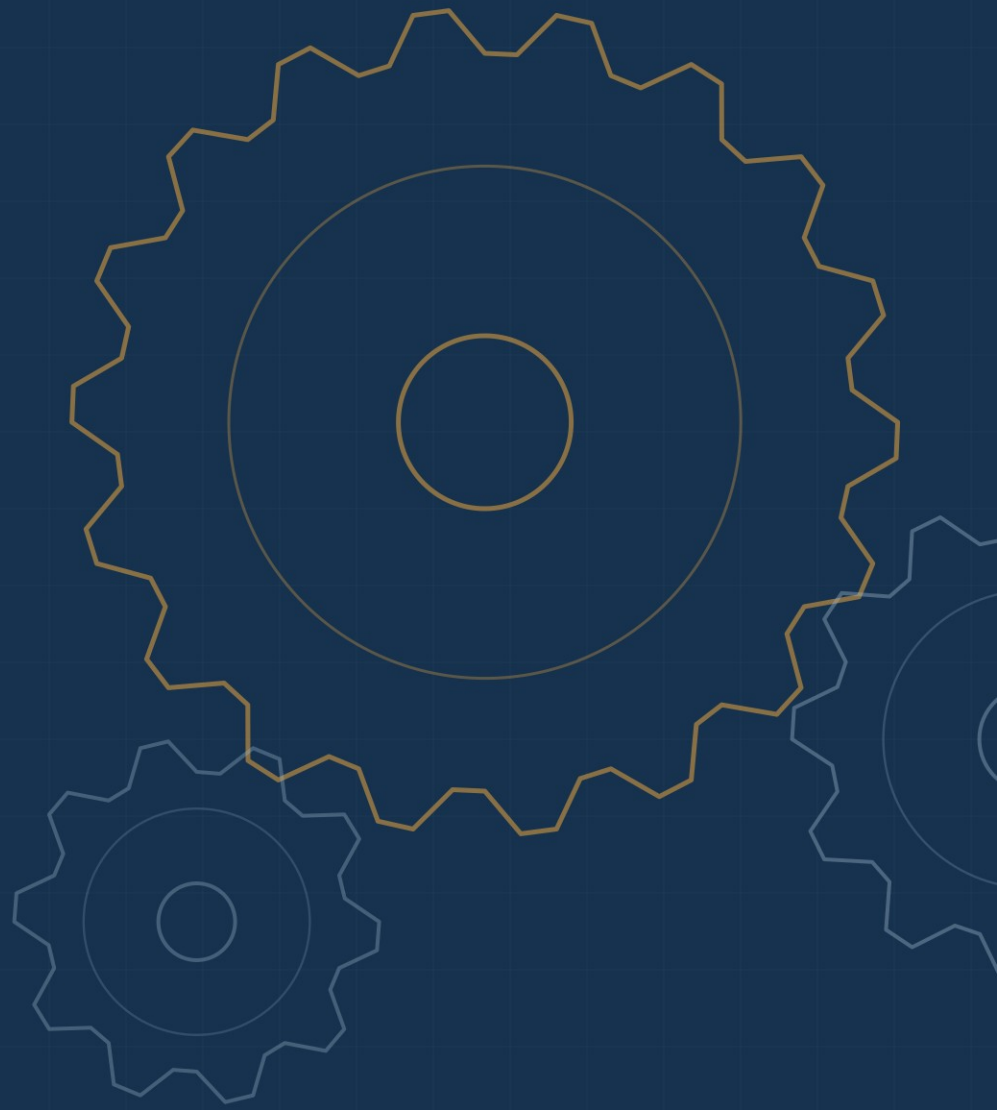
BASICS OF MACHINE OPERATION

Block 2 · Lecture 4 · 9 Dec 2026

Tribology and Lubrication; Fundamentals of Technical Diagnostics

dr inż. Radosław Gościniak

Akademia Techniczno-Artystyczna Nauk Stosowanych w Warszawie



Course plan

L1 Block 1 · 2 Dec 2026

Introduction to machine operation · Machines as technical means

L2 Block 1 · 2 Dec 2026

Systems approach · Maintenance organisation and strategies

L3 Block 2 · 9 Dec 2026

Modern maintenance · Availability, durability and wear

L4 Block 2 · 9 Dec 2026

Tribology and lubrication · Fundamentals of diagnostics

L5 Block 3 · 20 Jan 2027

Condition monitoring · Reliability fundamentals

L6 Block 3 · 20 Jan 2027

System reliability · Failure analysis and improvement

L7 Block 4 · 27 Jan 2027

Life data and maintenance logistics · Industry 4.0 · Review

Today: L4. Tribology and Lubrication; Fundamentals of Technical Diagnostics

RECAP

Before the break – six points

- **RCM** maintains functions; most failures are **not** age-related (Nowlan & Heap).
- **TPM**: 8 pillars, 5S, autonomous maintenance – everyone takes part.
- **OEE = A × P × Q** – shows where the losses are.
- A **CMMS** is only as good as its data.
- Availability: **Ai ≥ Aa ≥ Ao** – waiting time matters.
- Wear starts in the **surface layer**; economic wear → replace.

TODAY

Plan for today

PART A

Tribology and lubrication

1. Tribology – the science of friction and wear
2. Friction
3. Wear mechanisms
4. Lubrication

PART B

Fundamentals of technical diagnostics

5. Diagnostics and its types
6. Identification of the technical state
7. Diagnostic parameters and signals
8. Diagnostic procedures and decisions

01

Tribology – the science of friction and wear

Why surfaces in contact decide about energy, durability and cost



What is tribology – and why does it matter?

Tribology (from Greek “tribos” – rubbing) is the science and technology of **interacting surfaces in relative motion**: friction, wear and lubrication.

1966

The term was introduced in the UK **Jost Report** – it showed huge savings possible through better tribology.

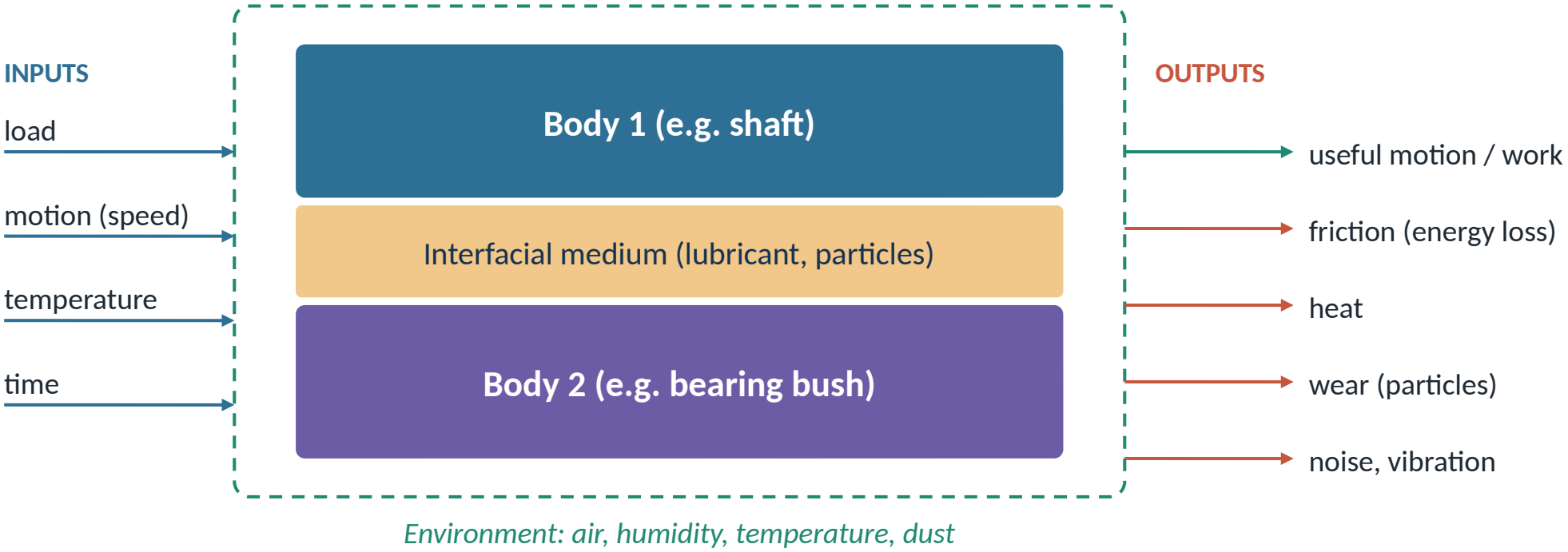
≈ 23%

of the world’s energy consumption originates from tribological contacts (Holmberg & Erdemir, 2017).

Most

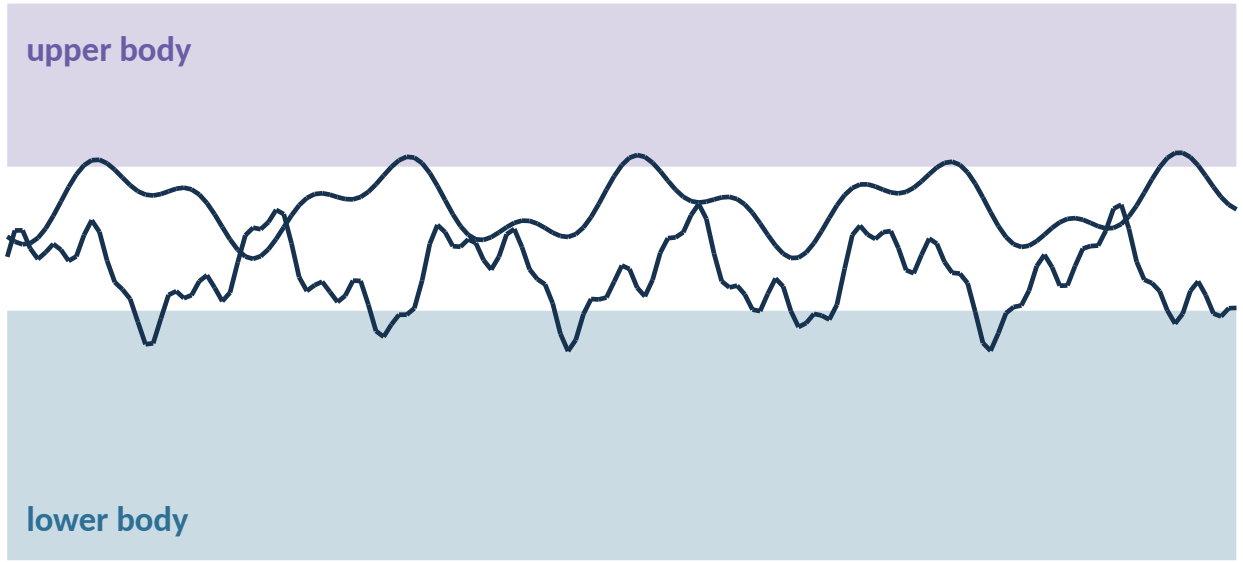
machine elements fail by **wear, fatigue or corrosion** of surfaces – not by breaking of the whole part.

The tribological system



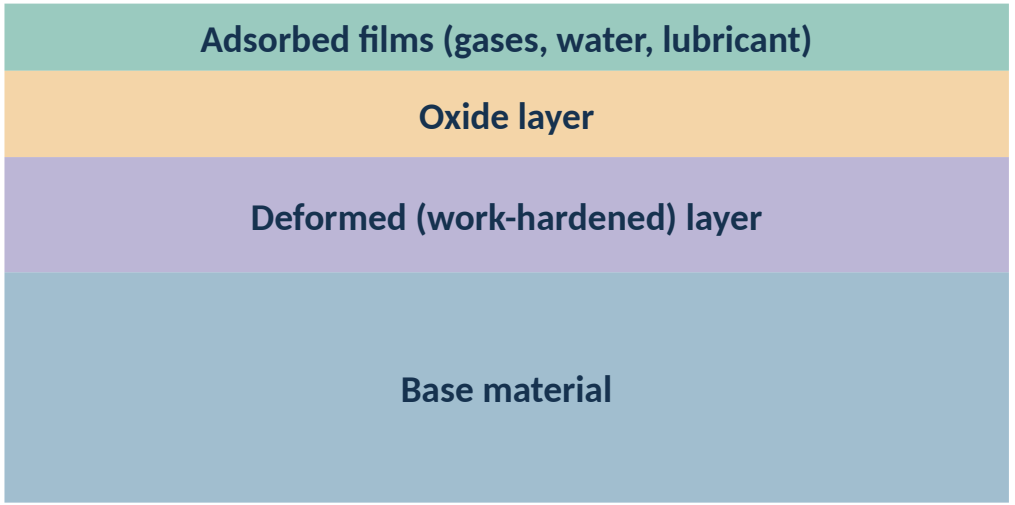
Friction and wear are **not properties of a material** – they are properties of the **whole tribological system**. The same steel can wear fast or slowly, depending on the partner, lubricant, load and environment.

Real surfaces – asperities and the surface layer



contact only at the tips of asperities

SURFACE LAYER (cross-section)

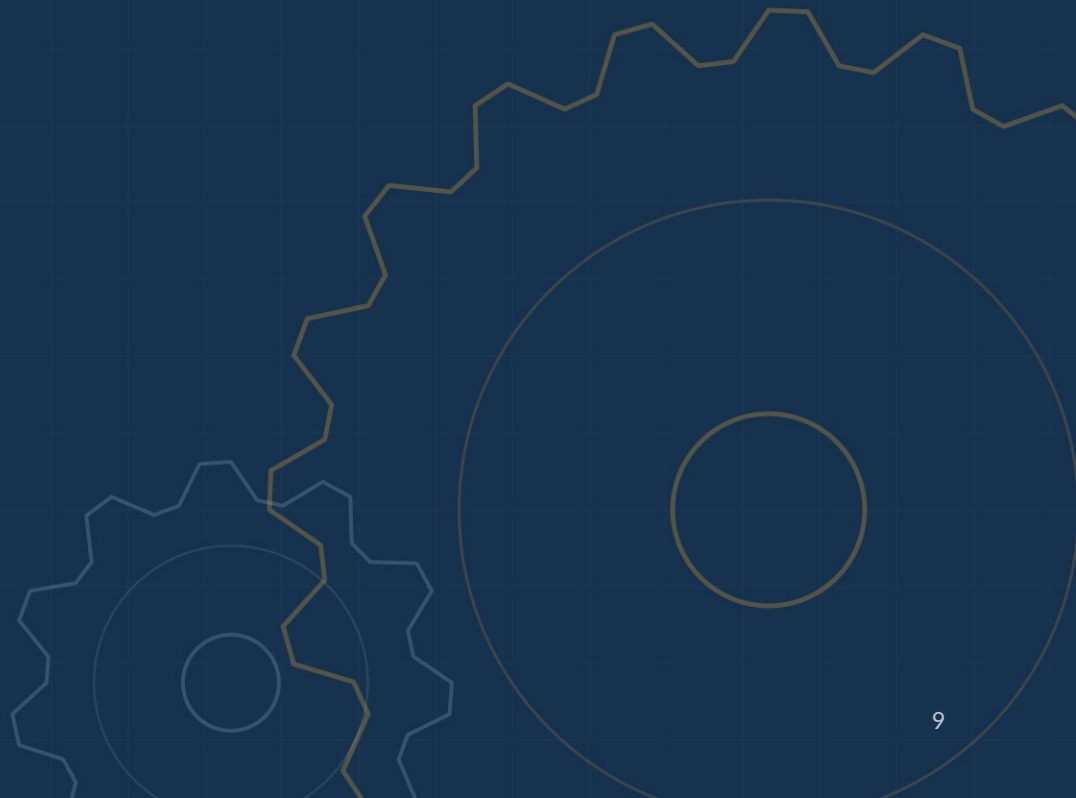


The **real contact area** is only a small fraction of the nominal area – so local pressures and temperatures at asperity tips are very high. Roughness is described by parameters such as **Ra** and **Rz** (ISO 21920, earlier ISO 4287).

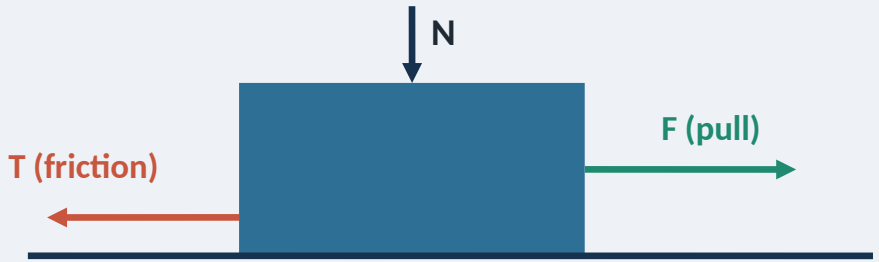
02

Friction

Laws of friction, types of friction and the Stribeck curve



The classical laws of friction



$$T = \mu \cdot N$$

Why not the area? Because the **real** contact area grows with load, not with the size of the block.

Amontons–Coulomb laws (17th–18th century):

1. friction force is **proportional to the normal load** N,
2. friction does **not** depend on the **apparent** contact area,
3. kinetic friction is nearly **independent of sliding speed**,
4. static friction (at rest) is **higher** than kinetic friction.

μ – coefficient of friction (dimensionless). These laws are good approximations for dry friction – not for lubricated contacts.

Types of friction

By motion: sliding friction

surfaces slide over each other – plain bearings, slideways, pistons.

By motion: rolling friction

a body rolls on a surface – rolling bearings, wheels, cam followers. Much lower resistance.

Dry and boundary friction

no lubricant, or only thin adsorbed films – high friction and wear (μ ≈ 0.1–1).

Mixed friction

the load is carried partly by the lubricant and partly by asperities – start-up, low speed, overload.

Fluid (hydrodynamic) friction

a full lubricant film separates the surfaces – very low friction (μ ≈ 0.001–0.01), almost no wear.

Internal friction

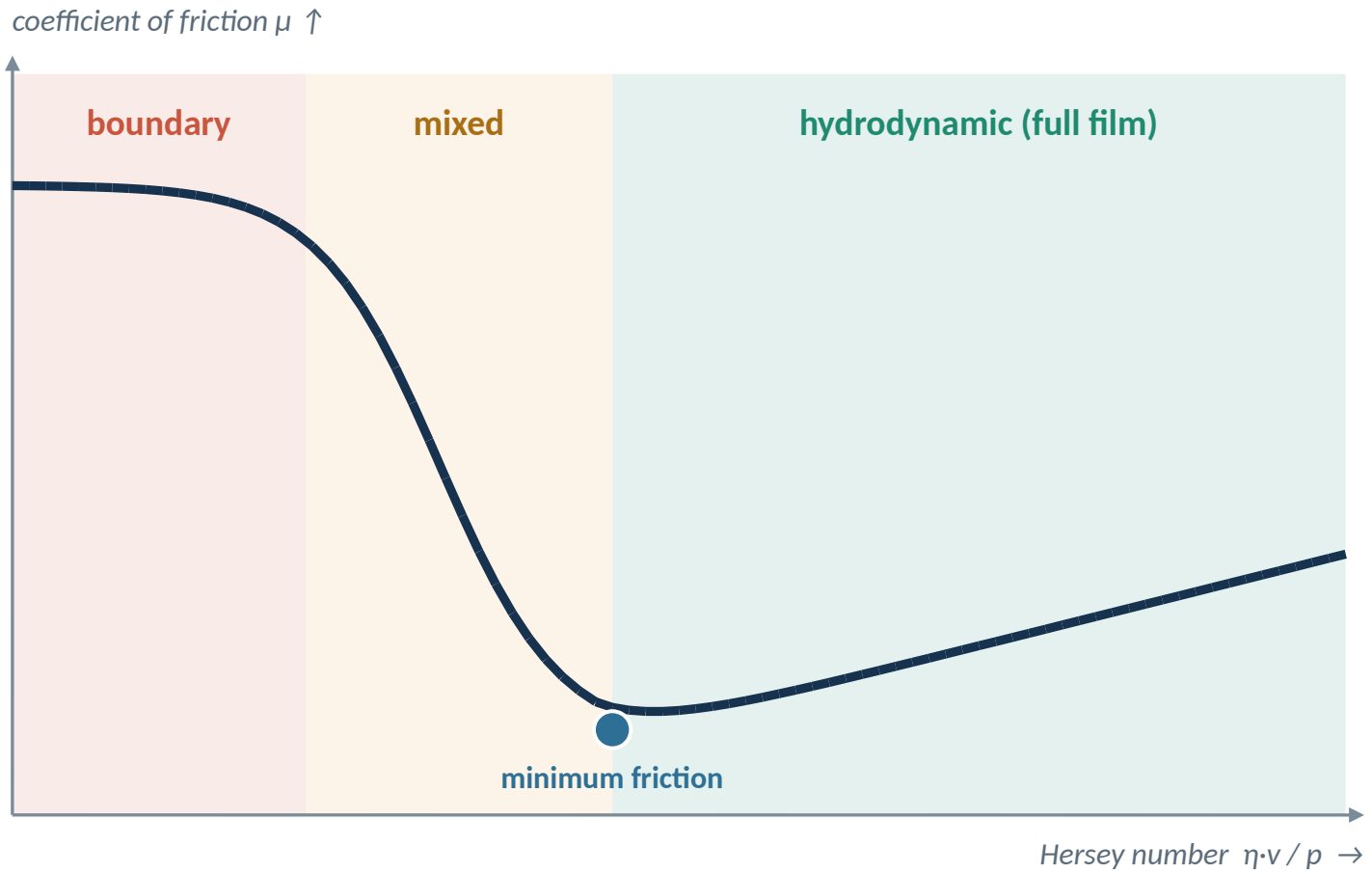
inside a material or fluid – damping, viscosity of the lubricant.

Typical coefficients of friction (orders of magnitude)

Contact	Coefficient μ	Comment
Steel on steel, dry	0.5 – 0.8	clean surfaces; risk of seizure
Steel on steel, boundary lubrication	0.1 – 0.2	thin film; start-up conditions
Steel on bronze, lubricated plain bearing	0.05 – 0.1	mixed friction
Hydrodynamic plain bearing (full film)	0.001 – 0.01	shaft “floats” on oil
Rolling bearing	0.001 – 0.005	rolling, with lubricant
PTFE (Teflon) on steel	0.04 – 0.1	self-lubricating polymer
Tyre on dry asphalt	0.7 – 1.0	friction is desired here!

Values are approximate and depend strongly on conditions – always check data for a specific application.

The Stribeck curve – lubrication regimes



η – lubricant viscosity, **v** – speed, **p** – pressure.

Low speed, low viscosity or high load → **boundary/mixed** friction → wear.

Higher speed or viscosity → **full film**; friction rises again slowly because of viscous drag.

Machines are designed to run just to the right of the minimum.

EXAMPLE

How much power does friction waste?

DATA – a machine tool slideway

- normal load on the slideway: **N = 5 kN**
- sliding speed: **v = 0.5 m/s**
- poorly lubricated: **μ = 0.15**
- well lubricated: **μ = 0.05**

$$P = T \cdot v = \mu \cdot N \cdot v$$

Poor lubrication

$$0.15 \times 5000 \times 0.5 = 375 \text{ W}$$

Good lubrication

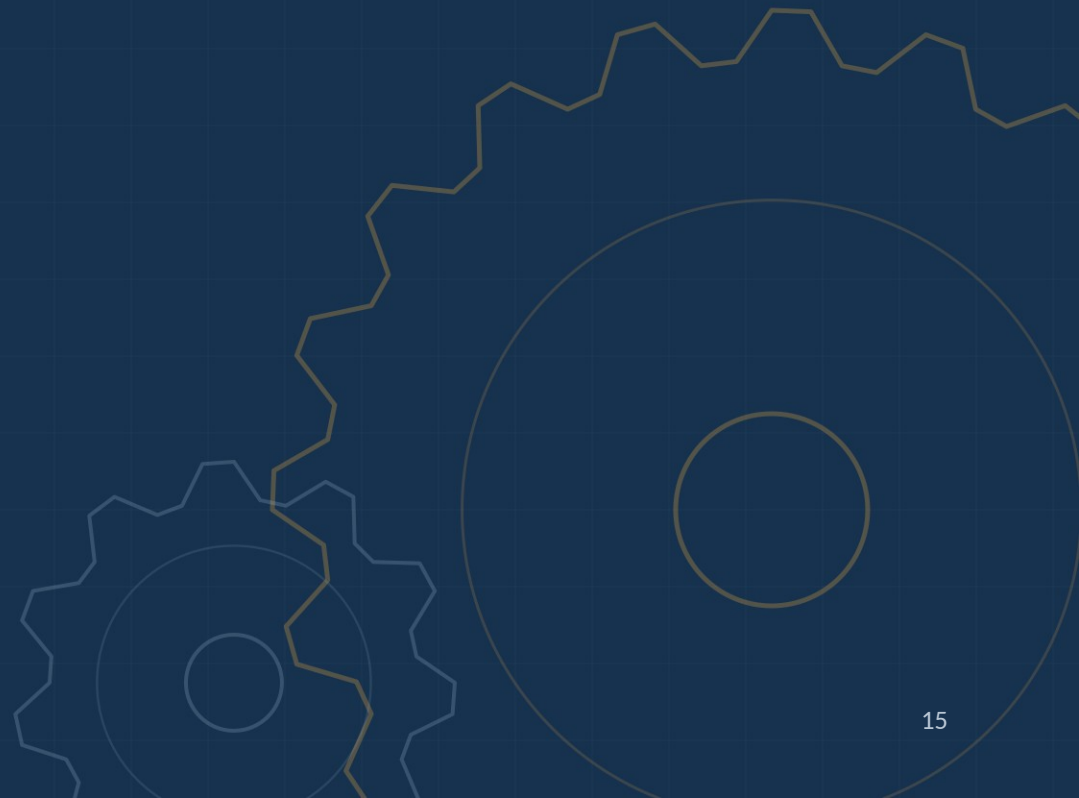
$$0.05 \times 5000 \times 0.5 = 125 \text{ W}$$

Good lubrication saves **250 W** – that is **3× less** heat. The heat goes into the slideway → **thermal expansion** → loss of machining accuracy, and faster wear.

03

Wear mechanisms

Adhesion, abrasion, fatigue and tribochemical reactions



Four basic wear mechanisms

Adhesive wear

micro-welding of asperities and tearing out of material – scuffing, galling, seizure.

Abrasive wear

hard particles or hard asperities cut and plough the softer surface – scratches, grooves.

Surface fatigue

repeated contact stresses create subsurface cracks → pitting and spalling (bearings, gears).

Tribochemical (corrosive) wear

chemical reaction with the environment + mechanical removal of reaction products.

Special forms: **fretting** (small oscillating movements), **erosion** (particles in a fluid stream), **cavitation** (collapsing vapour bubbles), **electrical erosion** (current through bearings).

Adhesive wear – scuffing and seizure

Mechanism	under high pressure, oxide and lubricant films break; clean metal asperities micro-weld and are torn out
Where	pistons and cylinders, plain bearings, gear teeth at high load, slideways, threaded joints
Symptoms	material transfer, torn surfaces, sudden rise of friction and temperature – in the worst case seizure
Prevention	good lubrication (EP additives), different materials in a pair, surface treatment, correct running-in, avoid overload

Abrasive wear – scratching and ploughing

Mechanism	two-body: hard asperities cut a softer surface; three-body: hard particles between the surfaces roll and cut
Where	agricultural, mining and construction machines; any system with dirty oil or dust
Symptoms	parallel scratches and grooves in the direction of motion; increased clearance
Prevention	filtration of oil and air, good seals, harder surfaces (hardening, coatings), clean assembly

Surface fatigue – pitting and spalling

Mechanism	repeated Hertzian contact stresses → cracks start below the surface and grow → small pieces break out
Where	rolling bearings, gear teeth, cams, rails and wheels
Symptoms	small pits (pitting) or larger flakes (spalling); rising vibration and noise – detectable early by diagnostics
Prevention	correct load and fit, clean lubricant of the right viscosity, good alignment, high material quality

Tribochemical wear and special forms

Tribochemical (corrosive)

oxidation or chemical attack, then removal by rubbing. Water in oil, acids, high temperature.

Fretting

very small oscillating movements in “fixed” joints – press fits, bolted joints, splines. Red-brown oxide powder.

Erosion

solid particles in a flowing fluid hit the surface – pump impellers, pipe bends, nozzles.

Cavitation

vapour bubbles collapse near the surface – pumps, propellers, hydraulic valves. Spongy, pitted surface.

Electrical erosion

electric current passes through bearings (e.g. inverter-fed motors) – fluting marks on raceways.

Combined wear

in real machines mechanisms usually act together – one mechanism often starts another.

EXAMPLE

Estimating wear – Archard's law

$$V = \frac{K \cdot F \cdot s}{H}$$

V – worn volume [m^3]
K – wear coefficient (dimensionless)
F – normal load [N]
s – sliding distance [m]
H – hardness of the softer material [Pa]

EXAMPLE – a sliding guide

- F = 1 000 N, s = 10 km = 10^4 m
- H = 2 GPa = $2 \cdot 10^9$ Pa
- K = 10^{-5} (lubricated, moderate wear)

$$V = 10^{-5} \cdot 1000 \cdot 10^4 \,/\, (2 \cdot 10^9)$$

$$\boldsymbol{V = 5 \cdot 10^{-8}\ m^3 = 50\ mm^3}$$

Wear grows **linearly** with load and distance and **falls** with hardness. Dry contact (K ≈ 10^{-3}) would give **100 times** more wear.

GROUP EXERCISE

ACTIVITY

Which wear mechanism is it?

Work in pairs for **6 minutes**. For each case, name the main wear mechanism and one preventive action.

1. Excavator bucket teeth wear quickly when digging sandy soil.
2. A pump impeller looks “spongy” with many small holes; the pump is noisy at low inlet pressure.
3. Small flakes broke out from the inner raceway of a rolling bearing after 3 years.
4. An engine piston seized after the oil pump failed.
5. Red-brown powder appears at the press-fit between a shaft and a gear hub.
6. Bearings of an inverter-fed motor have regular grey stripes on the raceway.

ANSWERS

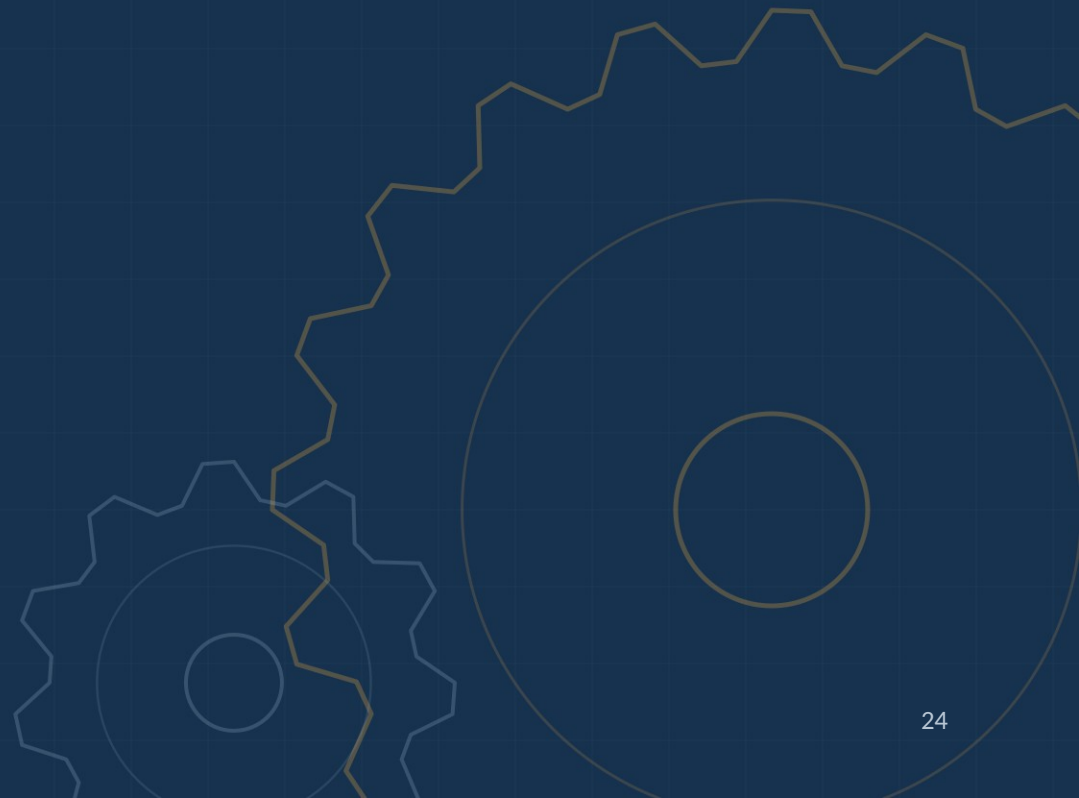
Which wear mechanism is it? – solution

Case	Mechanism	Preventive action
1. Excavator bucket teeth	abrasive wear	hardfacing, replaceable wear-resistant teeth
2. Spongy pump impeller	cavitation	increase inlet pressure (NPSH), avoid throttling the suction
3. Flakes on bearing raceway	surface fatigue (spalling)	correct load and lubrication; vibration monitoring
4. Seized piston	adhesive wear (seizure)	oil pressure monitoring and alarm; maintenance of the oil pump
5. Powder at a press fit	fretting (fretting corrosion)	tighter fit, better clamping, anti-fretting compound
6. Stripes on inverter-motor bearings	electrical erosion (fluting)	shaft grounding ring, insulated or ceramic bearings

04

Lubrication

Lubricants, viscosity, methods and good practice



Why do we lubricate? – six functions

Reduce friction
less energy loss and heat

Reduce wear
separate surfaces by a film

Cool
carry heat away from the contact

Protect
against corrosion and oxidation

Clean
carry wear particles and dirt to the filter

Seal
grease keeps dirt and water out

Types of lubricants

Oils

mineral (from crude oil) or synthetic (PAO, esters, PAG). Base oil + additives: anti-wear, EP, anti-oxidant, anti-corrosion, anti-foam. Good cooling, can be filtered.

Greases

oil held in a thickener (e.g. lithium soap). Stays in place, seals against dirt – rolling bearings, open gears. Classified by NLGI consistency (000–6).

Solid lubricants

graphite, molybdenum disulphide (MoS_2), PTFE – for high temperature, vacuum, very low speed or where oil is not allowed.

Gas and special lubricants

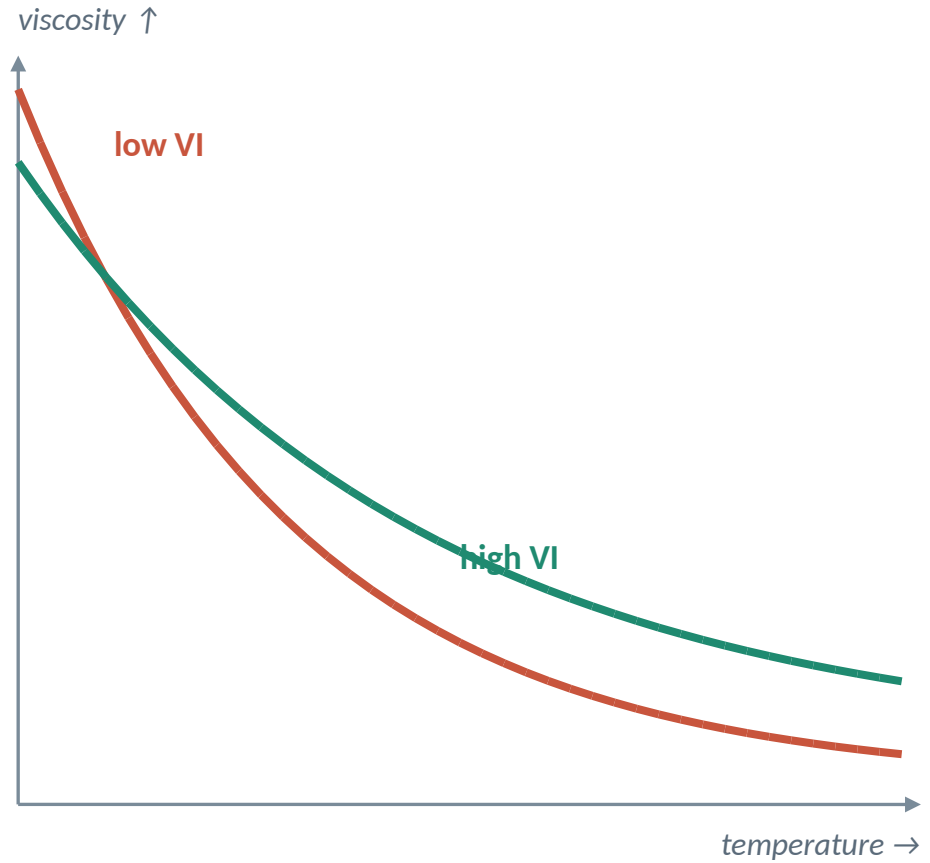
air or gas bearings, process fluids, water-based and biodegradable lubricants (food, forestry, marine).

Viscosity – the most important property of oil

Viscosity is the resistance of a fluid to flow. **Dynamic viscosity η** [Pa·s]; **kinematic viscosity ν = η/ρ** [mm²/s = cSt].

Industrial oils are classified by **ISO VG** grades (ISO 3448): the number is the mean kinematic viscosity at **40 °C** – e.g. ISO VG 46 ≈ 46 mm²/s.

Viscosity **falls strongly with temperature**. The **viscosity index (VI)** shows how much – a higher VI means a more stable oil.



Too low viscosity → no film, wear. Too high → energy loss, heat, poor flow at start.

Lubrication methods

Manual
oil can, grease gun – cheap, but depends on people; risk of over- or under-lubrication.

Oil bath and splash
gears dip into oil and splash it – gearboxes. Check oil level!

Circulating systems
pump, filter, cooler – turbines, large gearboxes, paper machines.

Single-point automatic lubricators
small cartridges that deliver grease for 1–12 months – remote bearings.

Centralised systems
one pump supplies many points via distributors – presses, conveyors, machine tools.

Oil mist / oil-air
very small amounts of oil in an air stream – high-speed spindles.

The five “rights” of lubrication and contamination control

1	**Right lubricant**	type, viscosity, additives – as specified by the manufacturer
2	**Right amount**	not too little (wear) and not too much (heat, seal damage)
3	**Right place**	clearly marked lubrication points – colour codes, labels
4	**Right time**	by plan or by condition
5	**Right method**	tools, clean procedure, trained people

Contamination control

Dirt and water are the main enemies of lubricants – a large share of bearing failures is linked to **contamination** and **poor lubrication**.

- store oils closed, dry and clean,
- use clean transfer containers and filter carts,
- breathers with desiccant on tanks,
- measure cleanliness – e.g. **ISO 4406** code.

EXAMPLE

How much grease does a bearing need?

$$G = 0.005 \cdot D \cdot B$$

G – grease [g], D – outer diameter [mm], B – width [mm]

A rule of thumb from bearing manufacturers for the **replenishment** quantity.

Over-greasing is a common mistake: the bearing churns the grease → temperature rises → grease degrades, seals can be damaged.

EXAMPLE – deep groove ball bearing 6310

- bore d = 50 mm
- outer diameter **D = 110 mm**
- width **B = 27 mm**

$$G = 0.005 \cdot 110 \cdot 27 \approx 15\ g$$

A typical grease gun gives about **1–1.5 g per stroke** → about **10–15 strokes**. Check your grease gun – the value differs between models!

A lubrication plan – example

Point	Lubricant	Method	Interval	Quantity	Who
Main motor bearings (2)	Li-complex grease NLGI 2	grease gun	2 000 h	15 g each	maintenance
Gearbox	gear oil ISO VG 220	oil bath – check level	weekly check; change 8 000 h	to the mark	operator / maint.
Slideways	slideway oil ISO VG 68	central system	automatic	per cycle	check tank: operator
Chain drive	chain spray	manual	weekly	thin film	operator
Hydraulic unit	hydraulic oil ISO VG 46	circulating	oil analysis every 6 months	–	maintenance

Illustrative plan for a machine tool. In practice, it is stored in the CMMS and lubrication points are marked on the machine.

Plain bearings and rolling bearings

Plain (sliding) bearings

sliding friction; hydrodynamic film at speed. **+** quiet, high load and shock capacity, compact, long life with a full film. **–** higher starting friction, need constant lubrication. Turbines, engines, large slow machines.

Rolling bearings

rolling friction; elastohydrodynamic (EHL) film. **+** low starting friction, standardised, easy to replace, little lubricant. **–** limited fatigue life, sensitive to contamination and shocks, noisier. Most machines.

Fatigue life of rolling bearings (L_{10}, ISO 281) is calculated – this connects tribology with reliability (Lecture 5).

Surface engineering against wear

Hardening
induction or flame hardening of the surface layer – shafts, gears, guides.

Thermo-chemical treatment
carburising, nitriding – harder, fatigue-resistant surface.

Thin hard coatings
PVD/CVD: TiN, CrN, DLC – cutting tools, moulds, engine parts.

Thermal spraying and cladding
thick wear-resistant layers – also for regeneration of worn parts.

Surface finishing
grinding, honing, polishing – lower roughness, better running-in.

Polymers and composites
self-lubricating bushings, PTFE – where oil is not possible.

CASE STUDY

Case study: the gearbox that failed after the oil change

Week 0	Oil changed during a weekend shutdown. A drum of “similar” oil from another machine was used – ISO VG 68 instead of VG 220.
Week 2	Operators notice higher noise. Temperature +15 °C. Nobody reports it – “new oil needs time”.
Week 5	Gear teeth show scuffing and pitting. Oil is dark and full of metal particles.
Week 6	Gearbox fails. 4 days of downtime, new gear set, cost many times the price of the right oil.

Lessons:

- too low viscosity → no film → **adhesive wear and fatigue**,
- missing **lubrication chart** and labels,
- early symptoms (noise, temperature) were ignored,
- a simple **oil analysis** or vibration check would have shown the problem.

Tribology and sustainability

Energy

lower friction in engines, gearboxes and bearings directly reduces energy use and CO_2 emissions.

Longer life

less wear = fewer spare parts, less waste, longer use of machines – circular economy.

Better lubricants

longer oil life with condition-based oil changes; biodegradable lubricants where leaks reach nature.

Less waste oil

filtration and oil analysis instead of fixed oil changes – less used oil to dispose of.

QUIZ

Quiz 1 – tribology and lubrication

1 The term “tribology” was introduced in...

A) 1766, France | B) 1966, the Jost Report (UK) | C) 2011, Industry 4.0 | D) 1978, Nowlan & Heap

2 According to Amontons–Coulomb, friction force is proportional to...

A) the apparent contact area | B) the sliding speed | C) the normal load | D) the temperature

3 On the Stribeck curve, the lowest friction is at the transition to...

A) boundary friction | B) dry friction | C) full-film lubrication | D) seizure

4 Pitting of gear teeth is caused mainly by...

A) abrasion | B) surface fatigue | C) corrosion | D) erosion

5 ISO VG 46 means a kinematic viscosity of about 46 mm^2/s at...

A) 0 °C | B) 20 °C | C) 40 °C | D) 100 °C

ANSWERS

Quiz 1 – answers

1 The term “tribology” was introduced in...

A) 1766, France | **B) 1966, the Jost Report (UK)** | C) 2011, Industry 4.0 | D) 1978, Nowlan & Heap

2 According to Amontons–Coulomb, friction force is proportional to...

A) the apparent contact area | B) the sliding speed | **C) the normal load** | D) the temperature

3 On the Stribeck curve, the lowest friction is at the transition to...

A) boundary friction | B) dry friction | **C) full-film lubrication** | D) seizure

4 Pitting of gear teeth is caused mainly by...

A) abrasion | **B) surface fatigue** | C) corrosion | D) erosion

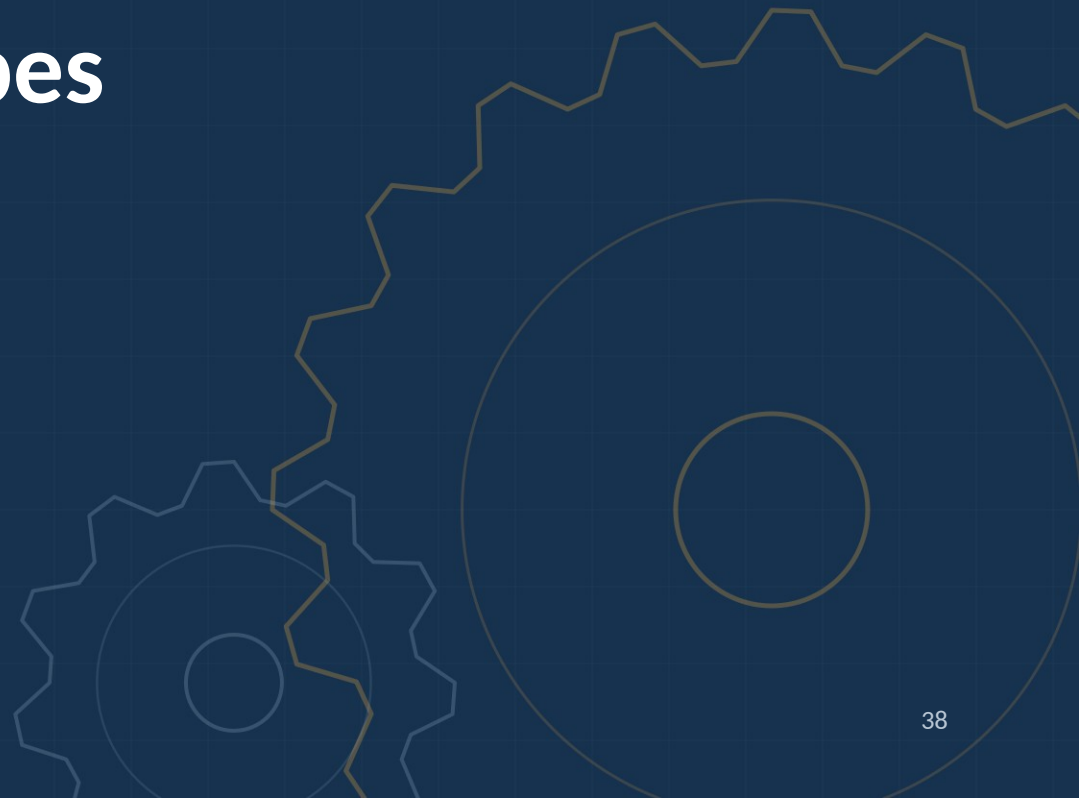
5 ISO VG 46 means a kinematic viscosity of about 46 mm^2/s at...

A) 0 °C | B) 20 °C | **C) 40 °C** | D) 100 °C

05

Technical diagnostics and its types

Recognising the state of a machine – in every phase of its life



Diagnostics – recognising the state of things

The word **diagnostics** comes from the Greek word “diagnosis” – recognition, distinguishing, judging. Today diagnostics is a recognised field of knowledge that **recognises the state of an object** by classifying it to a known type, explaining it by causes and purposes, determining its present phase and predicting its further development.

Technical diagnostics has developed very fast. A new impulse came from joining two groups of researchers: **model-based diagnostics** from automation and robotics, and **machine design and operation**.



KEY TAKEAWAY

Diagnostics answers: **what** is the state, **why**, and **what next**.

Technical diagnosing

Technical diagnosing is a process that determines the **current** technical state of a device – whether it is fit or unfit, how worn its parts are, how big the damage is. In practice it includes:

- testing, identifying and classifying developing damage and its **symptoms** (a symptom is an active feature of a diagnostic signal that reflects a specific type of damage),
- developing methods and means for testing and selecting symptoms,
- making **diagnostic decisions** about the state of the object – and about its use or the necessary preventive work.



KEY TAKEAWAY

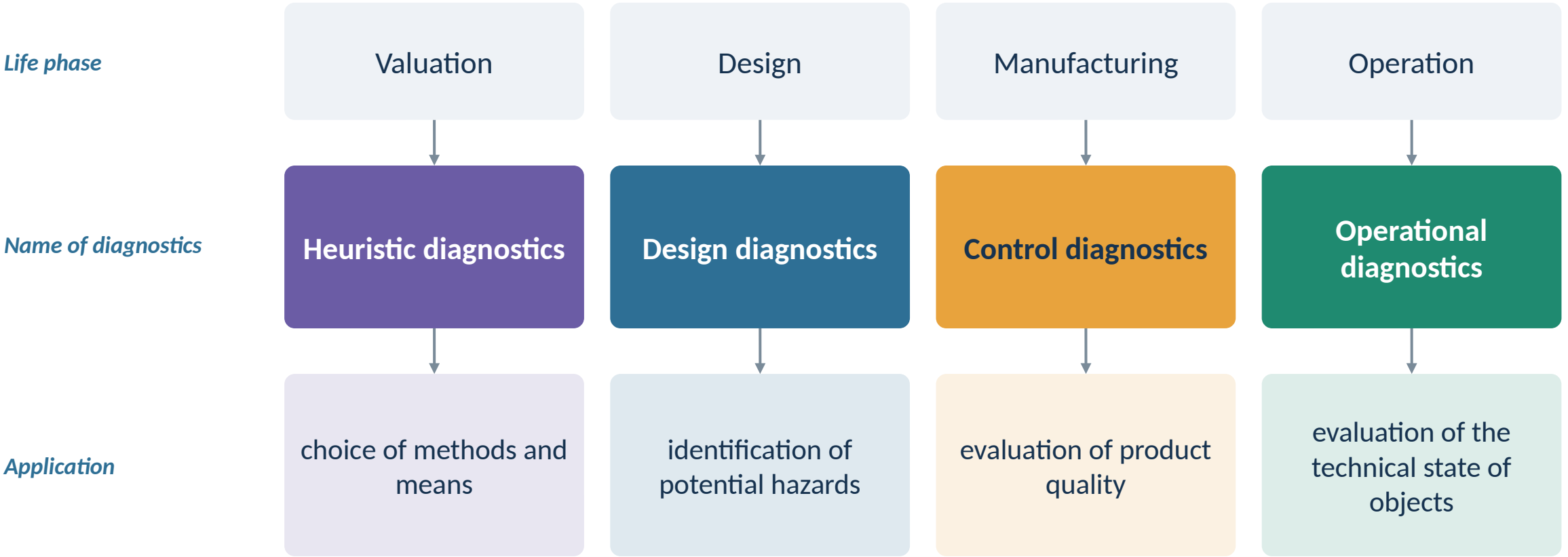
Symptom – an active feature of a diagnostic signal that reflects a specific type of damage.

Goals and places of diagnostics in the life cycle

0	VALUATION	**Goal:** choosing methods and means	**Where:** concept phase
1	DESIGN SPHERE	**Goal:** improve the quality of machines, incl. their diagnosability	**Where:** laboratory and test-site testing of prototypes; producers, R&D units
2	PRODUCTION SPHERE	**Goal:** improve the quality of manufacture	**Where:** final quality control of machines and assemblies; producers
3	OPERATION SPHERE	**Goal:** improve the operational quality of machines	**Where:** machines performing production tasks; users

Diagnostics accompanies the machine through its whole life – not only in operation.

Four types of technical diagnostics



In this course we focus on **operational diagnostics**.

Forms of operational diagnostics

A machine in operation has a structure defined by technical features that **degrade** during use. Their current values describe its technical state. Operational diagnostics includes:



Diagnosing

recognising the state – locating the damage



Monitoring

continuous observation of a machine that is still fit



Genesis

looking for the causes of damage that has already happened



Prognosis

predicting the future state of the machine

Prognosis: prediction and projection

Prognosis about the future state of a machine can result from:

Prediction

inference from a model that takes into account **factors that will appear in the future** and change the machine's state (e.g. a planned higher load).

Projection

inference from a model based on the **known past trajectory** of the technical state (e.g. extrapolating a vibration trend).

The result of planning diagnostics for operation is usually a chapter in the **operating and maintenance instructions**.

Key terms in international practice (ISO 13372)

Condition monitoring

acquisition and processing of information that indicates the state of a machine over time.

Diagnosis

examination of symptoms to determine the nature of faults or failures (kind, location, extent).

Prognosis

estimation of time to failure and risk for existing and future failure modes – the **remaining useful life (RUL)**.

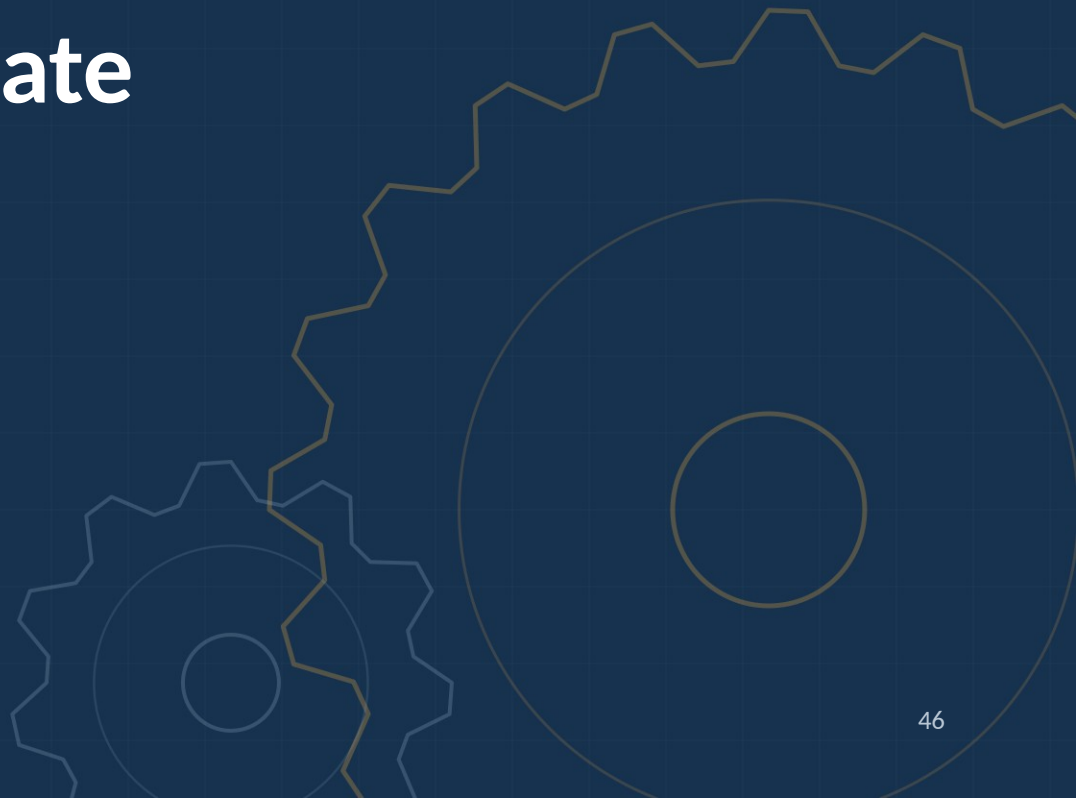
PHM

Prognostics and Health Management – combining monitoring, diagnosis and prognosis to support maintenance decisions.

06

Identification of the technical state

Up state, down state and the indirect observation of machines



Why do we need to know the technical state?

Technical devices consist of hundreds or thousands of parts. For example, a car has about **20 000 parts**, an aircraft about **4 million**. During use, wear processes change their designed properties.

Users must be able to evaluate these changes. The **technical state** is the set of technical properties that describe everything that happens with the object at time t. It is the result of the past – and we need it to predict the behaviour **now and in the future**.

It supports decisions about **further use**, **preventive actions** (adjustment, replacement of parts or assemblies) or **changes** in design or operation.



KEY TAKEAWAY

The technical state is the **result of the past** – and the basis for **decisions about the future**.

Up state and down state

The state changes continuously – there are infinitely many states. In practice, in the simplest case, we distinguish two classes:

Up state (fitness)
the device correctly performs its tasks

Down state (unfitness)
the device cannot perform its tasks

They correspond to two events: **serviceable** and **unserviceable**. “Fit/unfit” describe **states**, while “serviceable/unserviceable” describe concrete **events** that lead to them. EN 13306 uses “up state” and “down state”.

Three states – the example of a car

In operation practice, especially of vehicles, three states are often used:

Full fitness

the car is fully serviceable

Partial fitness

temporarily acceptable – e.g. an engine running on 2 of 3 cylinders, “limp-home” mode

Unfitness

unacceptable – e.g. driving without engine lubrication

Operational diagnostics usually **cannot measure** the state of a part directly (e.g. dimensions inside an assembled machine) – it works **indirectly**.

The diagnostic procedure for fit and unfit machines

When a machine is assembled, we cannot measure clearances or spring tension directly. We identify them **indirectly**, by testing the machine “as a whole”.

Machine in UP state



Machine in DOWN state

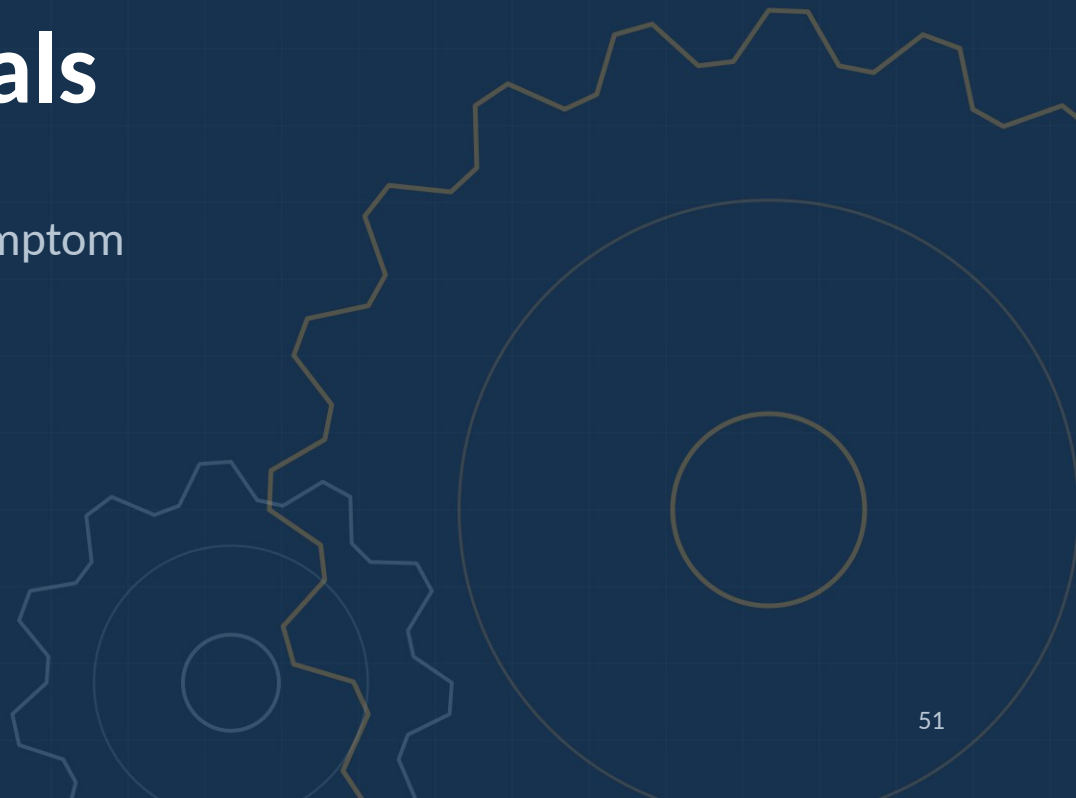


Causes of unfitness: misadjustment, damage, or the machine has reached the end of its life (overhaul or disposal).

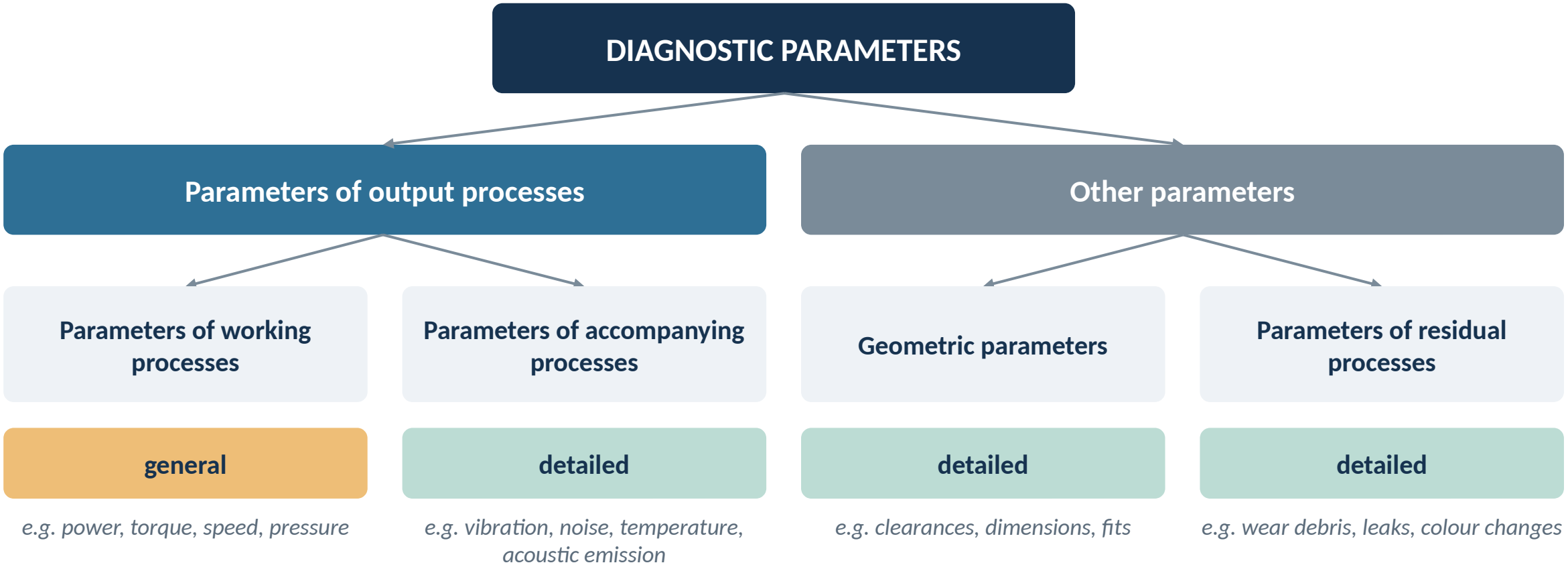
07

Diagnostic parameters and signals

What we measure, where it comes from, and what makes a good symptom



Classification of diagnostic parameters



Symptoms appear only when the object is damaged – e.g. overheated supply cables, excessive motor vibration, a discoloured resistor.

Three sources of diagnostic parameters

Diagnostic parameters can be obtained from three kinds of evaluation:

Working processes

continuous monitoring of their parameters: power, torque, speed, pressure.

Quality of products

dimensions, fits, joints. Assumption: the better the machine's state, the better the products.

Accompanying processes

physical and chemical symptoms in the outputs of a working machine – vibration, noise, acoustic emission, heat. The basis of vibroacoustics, thermography and others.

Types of diagnostic signals

Vibration
acceleration, velocity, displacement – unbalance, misalignment, bearings, gears

Acoustic
noise, ultrasound, acoustic emission – leaks, early bearing damage, cracks

Thermal
temperature, infrared images – friction, overload, bad electrical contacts

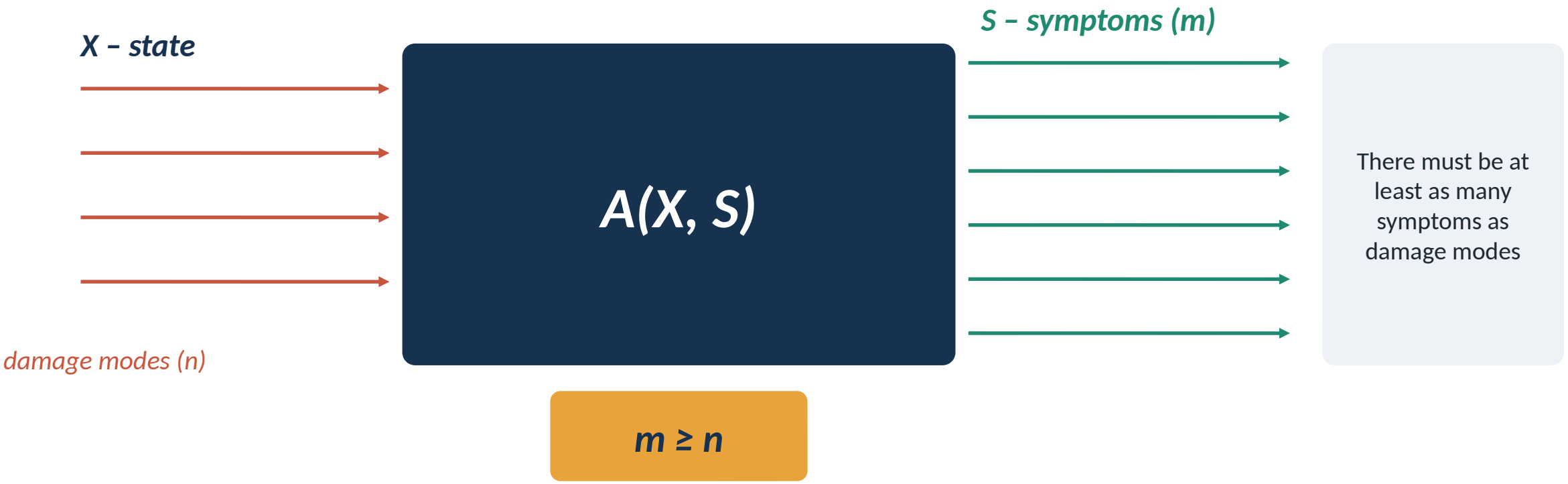
Tribological
oil condition, wear particles – lubrication and wear of gears and bearings

Electrical
current, voltage, insulation resistance – motors, drives, cables

Process / performance
pressure, flow, speed, power, product quality – overall efficiency

Observing state X through symptoms S

Operational diagnostics looks for relations between the machine state **X** and the diagnostic signals, recognised as symptoms **S** – the “black box” view:



One damage often shows several symptoms – e.g. a damaged bearing: higher housing temperature AND vibration.

From symptoms to diagnostic information

The state of the machine at a given moment can be described by a set of symptom values **S**. Often several symptoms inform about one damage – e.g. a bearing: higher housing temperature, vibration… This is important, because solving the diagnostic task requires **m ≥ n** – at least as many symptoms as damage modes.

After processing, the symptoms are shown as **measures** of values or waveforms (intensity). On this basis the operator **A** creates **diagnostic information** – statements about the state **X**.

Usually it concerns not the whole machine, but a specific **assembly**: the whole machine does not break – a specific assembly does, and this one is diagnosed.



KEY TAKEAWAY

The whole machine does not break – **a specific assembly** does, and this one is diagnosed.

What makes a good diagnostic parameter?

Sensitivity
a small change of state gives a clear change of the parameter

Unambiguity
one value of the parameter corresponds to one state

Wide range of change
large difference between new and worn state

Informativeness
carries much information about the state – ideally about the type of damage

Measurability
easy, safe and cheap to measure – ideally during operation

Repeatability
stable results in the same state and conditions

WORKED EXAMPLE

EXAMPLE

A diagnostic matrix for a gearbox

Damage mode ↓ / symptom →	Oil temp.	Vibration RMS	Spectrum: gear mesh	Spectrum: bearing freq.	Metal particles in oil	Noise
Gear tooth wear / pitting	○	●	●		●	●
Rolling bearing damage	○	●		●	○	○
Lack of oil / wrong oil	●	○	○	○	●	○
Shaft misalignment		●	○			○

● strong symptom ○ possible symptom

Vibration RMS alone reacts to almost everything – it **detects** a problem but does not **identify** it. The **spectrum** separates gear from bearing faults; oil analysis confirms wear. Here m = 6 ≥ n = 4.

EXERCISE

ACTIVITY

Car diagnostics: match symptoms to faults

Work in pairs for **5 minutes**. Match each symptom (1–5) to the most likely fault (A–E).

1	Squealing noise when braking	A	Flat / weak battery
2	Car pulls to one side on a straight road	B	Worn brake pads
3	Humming noise that grows with speed, changes when turning	C	Coolant leak
4	Temperature gauge rises; sweet smell	D	Low tyre pressure on one side
5	Engine cranks slowly in the morning	E	Damaged wheel bearing

EXERCISE

ANSWERS

Car diagnostics – solution

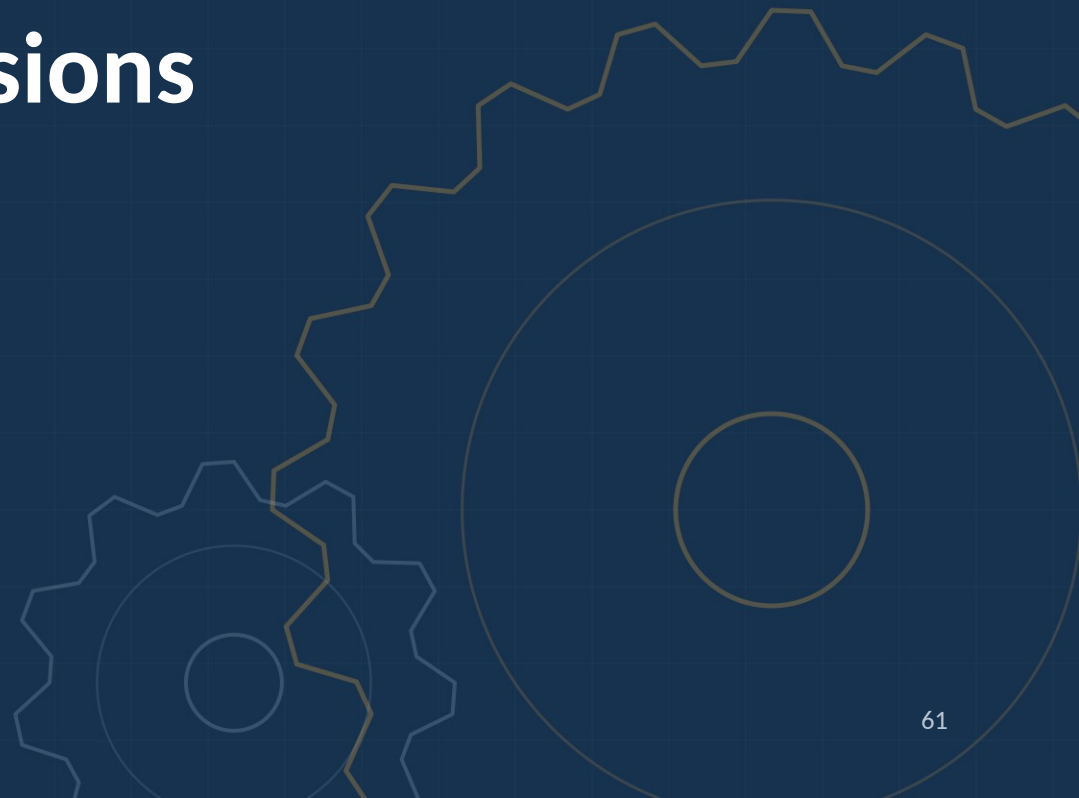
Symptom	Fault	Type of signal
1. Squealing when braking	B – worn brake pads (wear indicator)	acoustic
2. Pulls to one side	D – low tyre pressure on one side	performance / behaviour
3. Humming growing with speed	E – damaged wheel bearing	acoustic / vibration
4. Temperature rises, sweet smell	C – coolant leak	thermal + chemical
5. Slow cranking in the morning	A – flat or weak battery	electrical

A driver is the first diagnostician – most symptoms are noticed by people before any sensor.

08

Diagnostic procedures and decisions

From the signal to a decision – thresholds, trends and errors



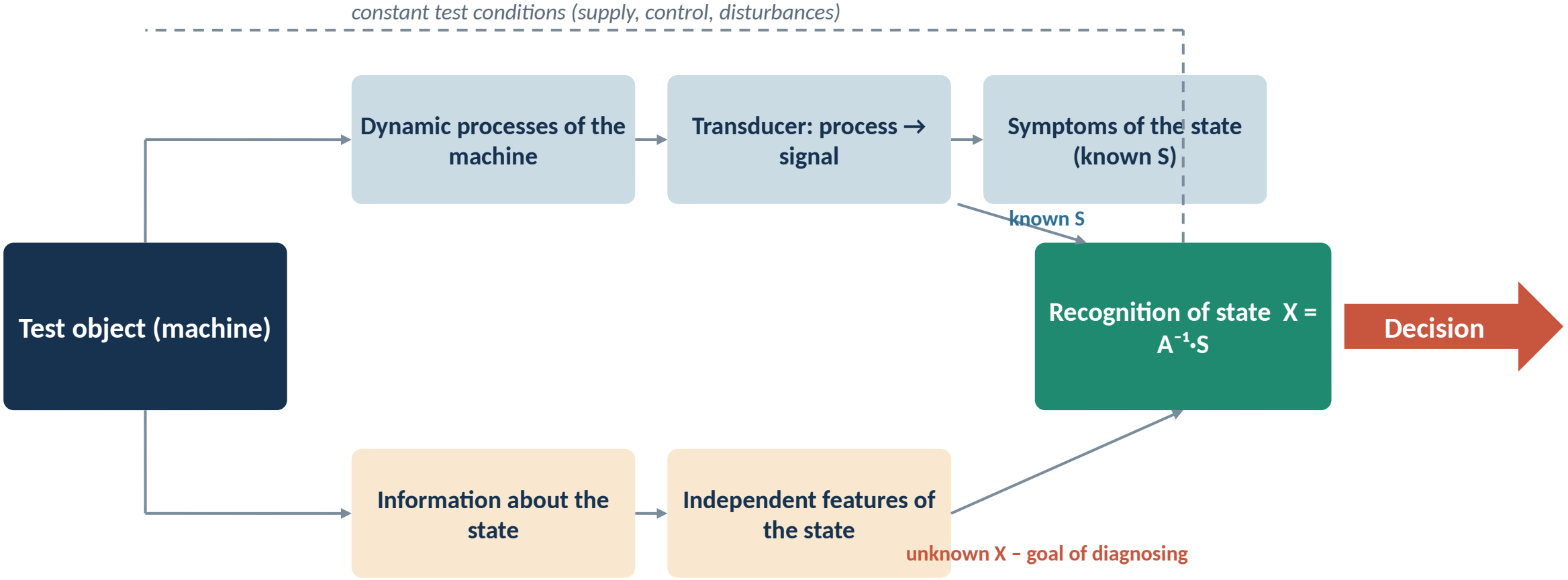
The diagnostic procedure – three activities

The technical state can be evaluated from measured diagnostic parameters **if we know the relations** between structural parameters (or states) and diagnostic parameters. These relations define the procedure.

A **procedure** (ISO 9000) is a specified way to carry out an activity or process – who, what and how.



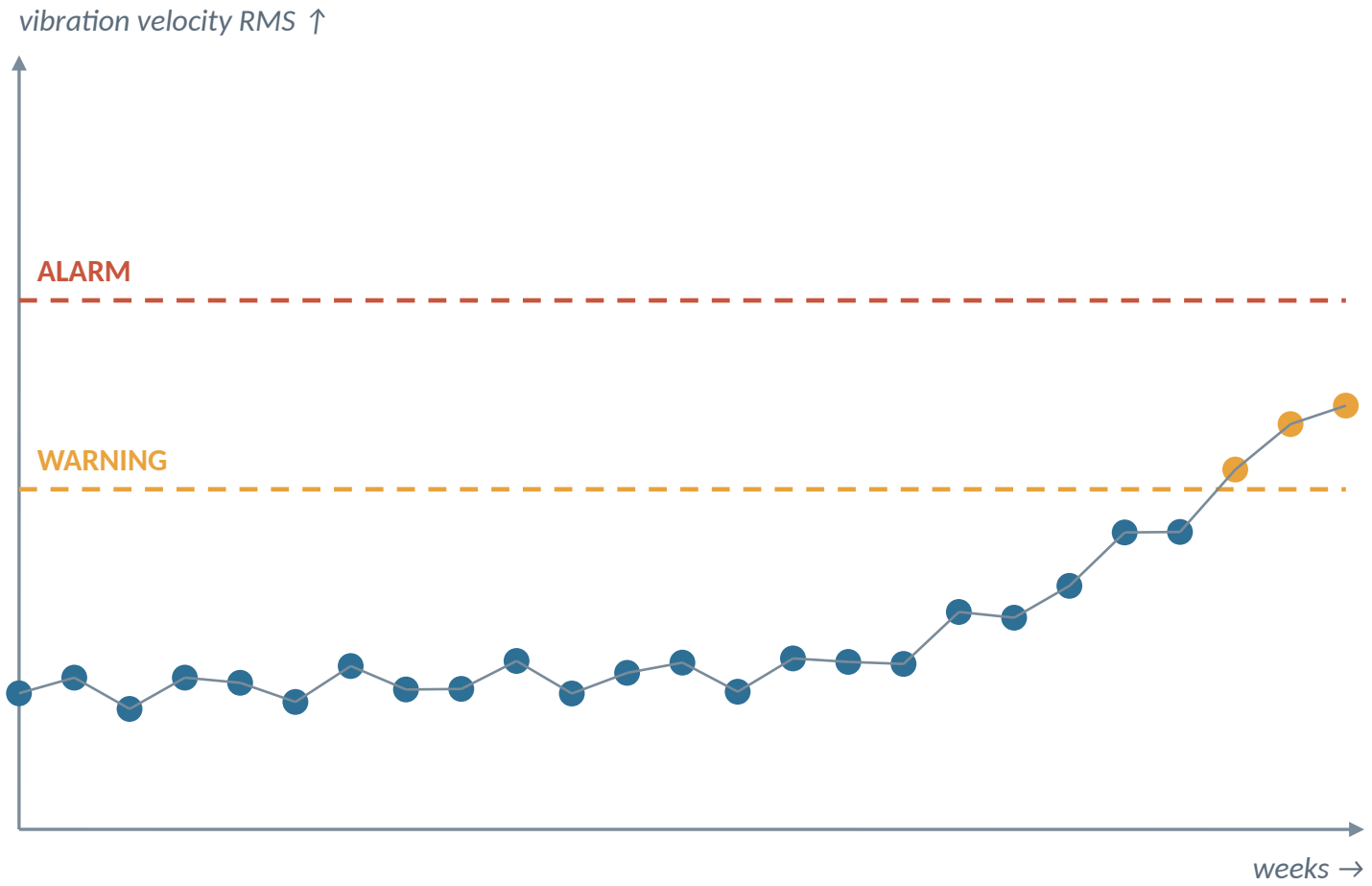
Elements of the diagnostic procedure



We know the symptoms S; we want the state X. The inverse of the relation A gives the diagnosis.

EXAMPLE

Thresholds and trends – an example



A fan is measured every week.

For months the level is **stable** (baseline).

Then a clear **upward trend** starts – long before the alarm.

Warning → plan the repair, measure more often. **Alarm** → act now.

A trend tells more than a single value.

Diagnostic errors: false alarm and missed fault

	Machine really OK	Machine really faulty
Diagnosis: OK	**correct ✓**	MISSED FAULT (type II error) – failure, danger, high cost
Diagnosis: faulty	FALSE ALARM (type I error) – unnecessary stop and repair	**correct ✓**

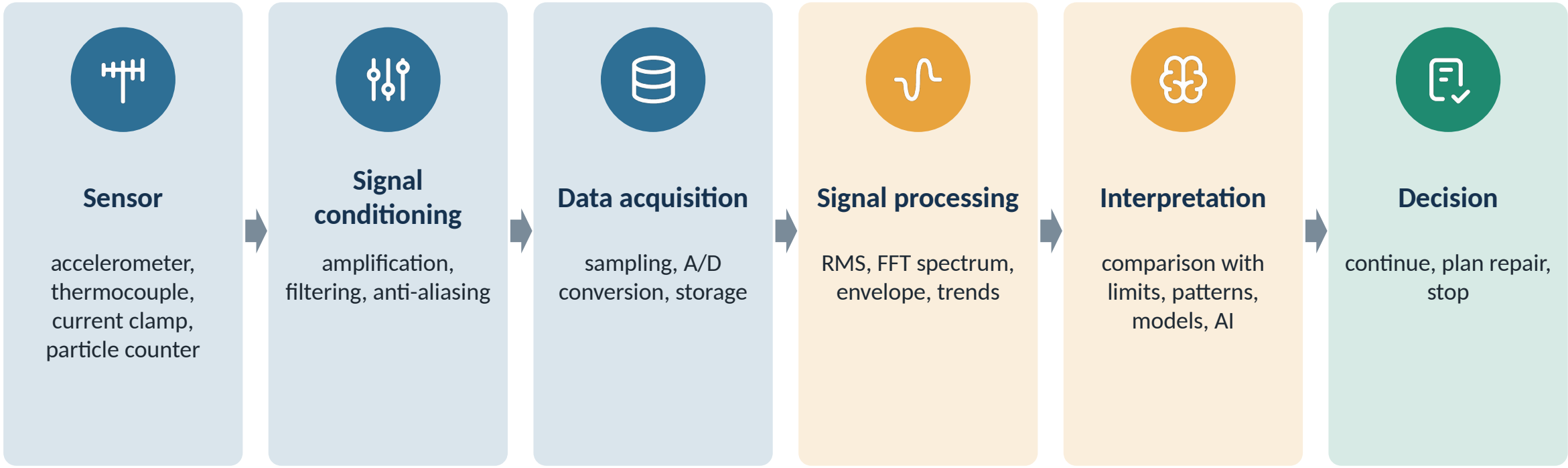
Every diagnostic decision has a risk of error.

A **lower threshold** → fewer missed faults, but more false alarms.

A **higher threshold** → fewer false alarms, but more missed faults.

For **safety-critical** machines we accept more false alarms.

The measurement chain – from sensor to decision



Measurements can be **periodic (off-line)** – a technician with a portable instrument – or **continuous (on-line)** – permanently installed sensors. More in Lecture 5.

Periodic or continuous monitoring?

	Periodic (off-line)	Continuous (on-line)
How	route with a portable instrument	permanent sensors, data sent automatically
Cost per machine	low	higher (sensors, network, software)
Detects	slowly developing faults (long P-F interval)	also fast-developing faults; trends in real time
Typical use	many standard machines: fans, pumps, motors	critical machines: turbines, compressors, main drives
Needs	trained people, a route plan, discipline	IT infrastructure, alarm management, data analysis

Remember the rule from Lecture 2: measurement interval < P-F interval.

QUIZ

Quiz 2 – diagnostics

1 Looking for the causes of damage that has already happened is called...

A) monitoring | B) genesis | C) projection | D) prediction

2 For a solvable diagnostic task, the number of symptoms m and damage modes n must satisfy...

A) $m < n$ | B) $m = 0$ | C) $m \geq n$ | D) $n \geq 2m$

3 Operational diagnostics usually evaluates the state...

A) directly, by disassembly | B) indirectly, through signals | C) only by visual inspection | D) never

4 A lower alarm threshold usually leads to...

A) more missed faults | B) more false alarms | C) no change | D) no measurements

5 Which is NOT a feature of a good diagnostic parameter?

A) sensitivity | B) unambiguity | C) repeatability | D) high price

ANSWERS

Quiz 2 – answers

1 Looking for the causes of damage that has already happened is called...

A) monitoring | **B) genesis** | C) projection | D) prediction

2 For a solvable diagnostic task, the number of symptoms m and damage modes n must satisfy...

A) $m < n$ | B) $m = 0$ | **C) $m \geq n$** | D) $n \geq 2m$

3 Operational diagnostics usually evaluates the state...

A) directly, by disassembly | **B) indirectly, through signals** | C) only by visual inspection | D) never

4 A lower alarm threshold usually leads to...

A) more missed faults | **B) more false alarms** | C) no change | D) no measurements

5 Which is NOT a feature of a good diagnostic parameter?

A) sensitivity | B) unambiguity | C) repeatability | **D) high price**

SUMMARY

Key takeaways from today

Friction and wear are properties of the **tribological system**, not of a material.

Stribeck curve: boundary → mixed → full film. Run just right of the minimum.

Four mechanisms: **adhesion, abrasion, fatigue, tribochemical**.

Lubrication: the **five rights** + contamination control.

Diagnostics: diagnosing, monitoring, genesis, prognosis; **m ≥ n**.

Use **trends and thresholds** – and know the risk of false alarms and missed faults.

REVIEW

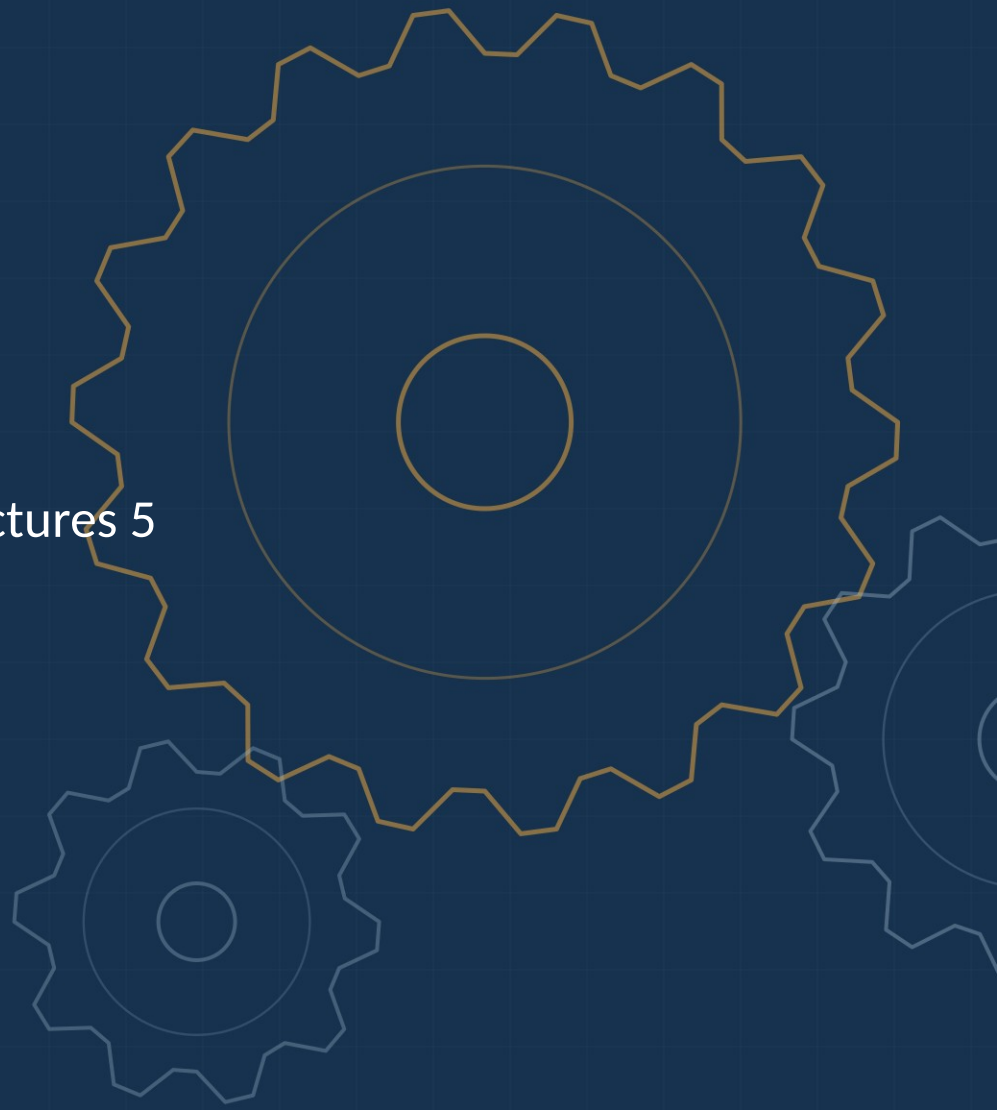
Review questions



1. What is a tribological system? Why are friction and wear not properties of a material?
2. Draw the Stribeck curve and describe the three lubrication regimes.
3. Describe adhesive, abrasive and fatigue wear: mechanism, symptoms, prevention.
4. Name the functions of lubricants and the “five rights” of lubrication.
5. Explain the forms of operational diagnostics and the condition m ≥ n.
6. What is the difference between a false alarm and a missed fault? How does the threshold influence them?

Thank you for your attention

Next: laboratory today 13:30 (R11) · next block 20 Jan 2027 – Lectures 5 and 6 · Merry Christmas and a Happy New Year!



dr inż. Radosław Gościniak