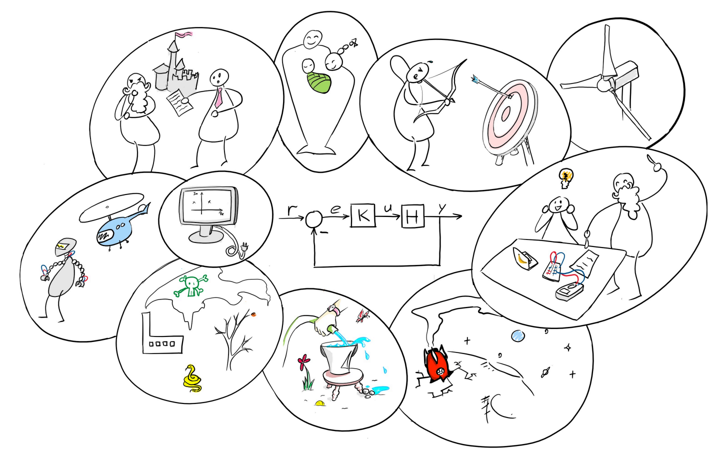
Anne Agata Brajkovic

Engineering Cybernetics Education Through Cybernetic Principles

A Case Study of the Engineering Cybernetics Education at NTNU

May 2021



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“*Progress is impossible without change, and those who cannot change their minds cannot change anything.*”

George Bernard Shaw

Abstract

The fundamentals of cybernetics cut across several traditional boundaries and play an essential role in the current high technological society. Proficient cybernetics engineers are valuable to Norway, but the engineering cybernetics education does not live up to it's potential. This thesis analyses the education offered by the Department of Engineering Cybernetics (ITK) at the Norwegian University of Science and Technology (NTNU). The method was twofold. In part one, an alternative way of introducing the theoretical aspects of cybernetics was presented. In part two, an overview of pedagogy that promotes learning was presented. The theory formed the basis for the case analysis of the engineering cybernetics education offered by ITK. The results show that education centred around the students and activities that promote learning produces more proficient engineers than the traditional education methods centred around a curriculum. The balance between research and teaching at ITK needs to be shifted in favour of education to obtain the goals. Changing the focus along these line requires an attitude change in teachers and students alike. It may be that the programme must be completely restructured and be built anew, or it may suffice to improve certain aspects of the education. Two specific opportunities for improvement were found to be communication and laboratory exercises. Better communication between teachers, students, and companies that hire graduated cybernetics engineers may provide students with more coherent and relevant knowledge. Optimising laboratory exercises may increase the students' overall skill, resulting in more proficient graduates. Some proposals to improved laboratory exercises are longitudinal labs across several subjects, lab-in-pocket, credits for student team participation, and open-ended real-life problems such as research and entrepreneurship. There is no blueprint to what measures are right for ITK. But by adopting the cybernetic principles and treating the programme like a closed-loop control system, correcting the education if the learning outcomes are not reached, it is possible to educate excellent engineers.

Sammendrag

Kybernetiske prinsipper skjærer over tradisjonelle faglige grenser og spiller en viktig rolle i dagens høyteknologiske samfunn. Dyktige kybernetikkingeniører er verdifulle for Norge, men utdannelsen innen teknisk kybernetikk lever ikke opp til potensialet. Denne oppgaven analyserer utdanningen som tilbys av Institutt for teknisk kybernetikk (ITK) ved Norges teknisk-naturvitenskapelige universitet (NTNU). Metoden var todelt. Første del tok for seg en alternativ måte å introdusere de teoretiske aspektene ved kybernetikk på. Del to presenterte pedagogikk som fremmer læring. Teorien dannet grunnlaget for caseanalysen av kybernetikkutdanningen som tilbys ved ITK. Resultatene viser at utdanning sentrert rundt studenter og aktiviteter som fremmer læring fører til dyktigere ingeniører enn de tradisjonelle undervisningsmetodene som er sentrert rundt en læreplan. Balansen mellom forskning og undervisning ved ITK må skiftes til fordel for utdanning for å oppnå målene. Endring av fokus langs denne linjen krever en holdningsendring hos undervisere og studenter. Det kan være at studieprogrammet må omstruktureres fullstendig og bygges på nytt, eller det kan være tilstrekkelig for å forbedre visse aspekter ved utdannelsen. To spesifikke forbedringsmuligheter ble funnet å være kommunikasjon og laboratorieøvelser. Bedre kommunikasjon mellom lærere, studenter og arbeidsliv kan gi studentene mer sammenhengende og relevant kunnskap. Optimalisering av laboratorieøvelser kan øke studentenes samlede ferdigheter, og resultere i dyktigere ingeniører. Noen forslag til forbedring er langsgående laboratorier på tvers av flere emner, lommelab, studiepoeng for deltakelse i studentorganisasjoner og virkelige prosjekter gjennom forskning og entreprenørskap. Det finnes ingen fasit for hvilke tiltak som er riktige for ITK. Men ved å bruke de kybernetiske prinsippene og behandle programmet som et lukket sløyfesystem og korrigere utdanningen hvis læringsutbyttet ikke oppnås, er det mulig å utdanne fremragende ingeniører.

Preface

This paper was made under the Department of Engineering Cybernetics (ITK) for the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, during the spring of 2021. The thesis has been submitted to the faculty of Information Technology and Electrical Engineering for the degree of Master of science.

The assignment is given by NTNU with Morten Dinhoff Pedersen as supervisor. The thesis is focused on the importance of cybernetic competence in Norwegian society. This thesis was meant to inform. It is not a manual on how to transition programmes to be student centred. Rather, it establishes a starting point from where institutions may make informed decisions about their education. The thesis is most suited for engineering cybernetics programmes, and especially the education offered by ITK. Still, other departments and institutions may use the thesis in part or in full. Further research into various aspects of the thesis is left to the stakeholders.

I wish to thank the contributors in the process – my supervisor Morten Dinhoff Pedersen for valuable assistance and guidance; the companies that answered my inquiries regarding graduated cybernetics engineers; and everyone else, faculty members and students alike answered emails and questions that have come their way.

Anne Agata Brajkovic

Trondheim, 31st May 2021

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Nomenclature

Programme	Description
ABET	Accreditation Board for Engineering and Technology
Cyb	Cybernetics and Robotics, MSc
Diku	Directorate for Internationalization and Quality Development in Higher Education (Direktoratet for Internasjonalisering og Kvalitetsutvikling i Høgare Utdanning)
EiT	Experts in Teamwork
Elsys	Electronic System Design and innovation, MSc
EPT	Department of Energy and Process Engineering (Institutt for Energi- og Prosessteknikk)
IES	Department of Electronic Systems (Institutt for Elektroniske Systemer)
IPM	Department of Mechanical Engineering and Production (Institutt for Maskinteknikk og Produksjon)
ITK	Department of Engineering cybernetics (Institutt for Teknisk kybernetikk)
NOKUT	National Body for Quality in Education (Nasjonalt Organ for Kvalitet i Utdanningen)
NTNU	Norwegian University of Science and technology (Norges Teknisk-Naturvitenskapelige Universitet)
SFU	Centres for Excellence in Education (Sentre for Fremragende Utdanning)

Abbrevation	Description
CDIO	Conceive Design Implement Operate
CL	Cooperative and Collaborative Learning
D	Derivative Effect (of controller)
I	Integral Effect (of controller)
ICT	Information and Communication Technology
LTI	Linear Time Invariant
MSc	Master of Science
P	Proportional Effect (of controller)
PBL	Problem Based and Project Based Learning
PI	Peer Instruction
STEM	Science, Technology, Engineering and Mathematics
SWOT	Strengths, Weaknesses, Opportunities and Threats

Variable	Description
A	Area
b	Initial conditions
c	Light speed
d	Dampening
e	Error
E	Energy
H	Process
I	Identity matrix
K	Controller
K_I	Integral controller
K_P	Proportional controller
m	Mass
r	Reference
r'	Modified reference
s	Complex number frequency parameter for Laplace
S	Deviations (avviksforhold??)
T	Filter
u	Input
y	Output
$\hat{y}$	Estimated output
w	Disturbances and model error

Chapter 1

Introduction

Around 0.06 per cent of Earth's population lives in Norway. Despite the small populace, the country has done well globally, benefiting from the goods the ocean has to offer (NHO, 2021). The Norwegian engineering cybernetics community has played an important part in this success by developing technology for locating and extracting petroleum from the seabed and is therefore globally recognised.

Technology has made humanity prosper, but reckless use has brought upon us global, potentially catastrophic challenges like extreme weather, weapons of mass destruction, pandemics and ecological collapse (Westin et al. 2020, World Economic Forum 2021). For humanity to continue to prosper, the strategies must be shifted to a more prudent approach, developing new and sustainable technology. If Norway is to excel, the country cannot continue to depend on fossil fuel export. On the other hand, engineering cybernetics and robotics can be further developed to tackle global challenges while creating new sustainable and humane jobs.

Norway collected riches from petroleum because it is a limited resource where, by chance, large amounts were found in the country's ocean space. Cybernetic engineers are by no means limited to Norway. On an international basis, there are millions of engineers. If Norway is to excel within this field, the engineers must be excellent and, therefore, the engineering education must be excellent.

In the last hundreds of years, the world has been revolutionised. The population has increased massively, enormous amounts of information is always accessible, and technology development and globalisation continue fast. But the classroom has changed little (Rugarcia et al. 2000, Johnson et al. 2014) in the same time frame. Even with a persistent call for change in the educational system, demanding teaching methods that more actively involve students in the learning process for more meaningful and long-lasting learning (See, e.g. Donovan et al. (2000), Ramsden et al. (2007), Ramirez-Mendoza et al. (2018)), the change is slow.

The Department of Engineering Cybernetics (ITK) at the Norwegian University of Science and Technology (NTNU) offers the country's foremost cybernetics studies (ITK 2021c). The Norwegian government (Kunnskapsdepartementet 2017) recognises the importance of education and states that universities and colleges must offer up-to-date and relevant educations that motivate learning. Despite this, The Wold University Rankings (2021) and QS Top univerities (2021) ranks the NTNU as number 150 of engineering and technology universities worldwide, which is okay, but certainly not excellent.

1.1 Scope and Delimitation

By collecting theory within cybernetics and pedagogy, this thesis examines the education offered by the Department of Engineering Cybernetics at NTNU and analyses how the department can provide state-of-the-art education that produces excellent, world-class engineers. The scope is answered by asking the following research questions:

1. What is cybernetics?
2. What are good pedagogical strategies for engineering education?
3. What is the current state of engineering cybernetics education at NTNU?
4. Which measures can be taken to optimise engineering cybernetics education at NTNU?

1.2 Structure

The nature of the scope is twofold, and the thesis has thus two theoretical chapters. First, the science of engineering cybernetics is analysed. Second, some pedagogical principles are explored. The two chapters create the foundation for a case on the engineering cybernetics education offered at NTNU. The case addresses the last two research questions. The most important results are discussed before a conclusion is reached.

Chapter 2

Cybernetics

Humans have tried to understand the world for ages. At first glance, the behaviour of men and animals, the spread of sickness and crop failures and the deposits of minerals may seem aimless. But as Penrose (2004, p. 5) stated,

> Do not seek for reasons in the specific patterns of stars, or of other scattered arrangements of objects; look, instead, for a deeper universal order in the way that things behave.

Engineers, scientists and philosophers have studied the world and found that the behaviour of the smallest ants to the largest planets, even the behaviour of humans and animals, might be described by mathematics. Moreover, the behaviour of humans and animals may be synthesised through mathematics and implemented in machines.

Human behaviour while driving a car, for example, can easily be described and synthesised. A person uses information about their surroundings – if it is windy, rainy or hills – together with their experience of driving in the past to make an informed decision on how hard they should press the gas pedal (cause) to drive at the desired speed (effect). This – initiating an informed cause to get the desired effect – is cybernetics. By connecting the actuator and a speed sensor to a computer and specifying the desired speed, it is possible to write a programme that automatically controls the car's speed. When computer programme automates human behaviour, engineering cybernetics is at work.

Both the person and the programme initiates a chain of causes and effects to get the desired speed. The cause and effect chain may thus be said to be inverted. Cybernetics can therefore be defined as the study of cause and effect and how the principle may be inverted to obtain the desired outcome.

Cybernetics is often taught by establishing the mathematical fundamentals first, defining the Laplace transform, matrix exponentials, and other necessary principles in a cybernetic analysis, before the actual controller eventually is found by trial and error. Learning the cybernetic behaviour becomes secondary to mathematical analyses, and the philosophical aspects of the science are neigh non-existent. This approach might be intuitive for experienced engineers but may not make much sense for newcomers to the field that have not yet learned *why* they learn abstract mathematics.

This chapter aims to present an alternative way of introducing the theoretical aspects of cybernetics. It is assumed that the reader of this thesis is experienced with cybernetic concepts. Nonetheless, the fundamentals of cybernetics will be derived as a proposition to an alternative way to teach the material. Instead of building the knowledge chronologically like is tradition, this derivation engages intuition and common sense, stating the goal before suggesting intuitive ways to reach the goal.

2.1 Tools for Cybernetic Analysis

Automatic systems depend on information to initiate the right causes. Disturbances from the entire Earth and even from the universe's outer reaches may influence the system. It is impossible to predict all unknown causes, nor would it be feasible to handle the data. There are endless amounts of information available at all times, making it impossible to make fully informed decisions. But as Beer (2002, p. 213) stated,

> [...] despite dealing with variables too many to count, too uncertain to express, and too difficult even to understand, something can be done to generate a predictable goal.

Limiting the variables and reducing a problem to a minimisation principle (Wiener 1985) by creating a model makes it possible to study control through the abstract. A model is a delimitation of reality to the essential elements of a system, a simplified representation of the world where all excess information is removed, as illustrated in Figure 2.1. In this case, the system is defined as the tap, the tank and the water flowing in. The system is cleared from the rest of the world by dashed system boundaries.

Figure 2.1: A model (right) is a simplified representation of reality (left). The dashed line represents the boundaries of the defined system.

Even though the butterfly flapping its wings or the watch's ticking may influence the system in some way, it is not feasible to predict the effects. Therefore, the butterfly, the wind, and other uncertain and unintended variables are included in the model as the disturbances w.

The system is still influenced by w, causing the actual effect to diverge from the intended effect. In the case of the car, the person and the cruise controller alike continuously check if the speed is optimal or if it is necessary to reconsider the input. When the car encounters a hill, the speed decreases. The person or the cruise controller will then reconsider the pressure on the gas pedal, pressing harder and again obtaining the correct speed.

The reason the world can be simplified to a model is that the system is allowed to reconsider. A model makes it possible to handle the data. By using mathematical tools, the future can, to some degree, be predicted as a system is brought to its desired ends.

2.1.1 Models

A common way to start a cybernetic analysis is by making a system model like in Figure 2.2. The input signal is the cause that starts the process. It may be denoted u and, in this case, represents the opening of the tap. The output signal is the effect of the process. It is usually named y and represents the water level in the tank. The process is named H in this case and is the flow of water into the tank. The process is what binds the cause and the effect.

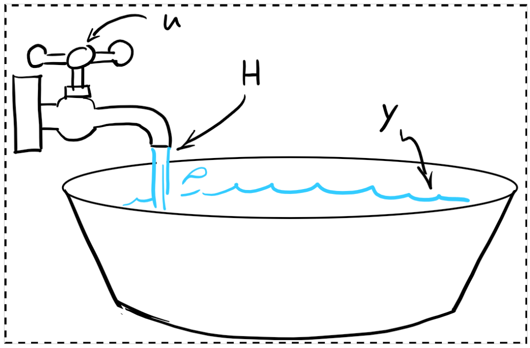

Figure 2.2: Turning on the tap causes the tank to fill up with water.

Though this is an illustrative model, there is a lot of excess information. The visual form of the tap is not essential, nor is the shape of the tank or the fact that the water is blue. The valuable information is the input, the process and the output. The model may be reduced to these salient elements in a block diagram, as in Figure 2.3. The block diagram graphically describes how the components of the system interact with each other.

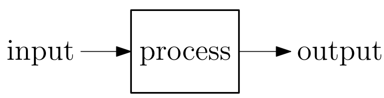

Figure 2.3: Block diagram representation of a system. Arrows represent signals and blocks represent processes.

The block diagram for the tank system is given in Figure 2.4a). Arrows represent signals, and blocks represent processes.

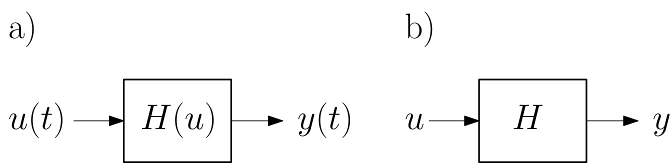

Figure 2.4: The essential elements of the system are included in a block diagram. Whilst the signals and processes are functions (a), they may be displayed as variables for simplicity (b).

The signals are functions of time (t), and the processes are functions of their input signals. Figure 2.4b) is used for simplicity, the argument being implicit.

Block diagrams form a basis for mathematical models, also describing how the elements of the system interact with each other. The mathematical model of the tank system may look like

$$y(t) = H(u(t)), \tag{2.1}$$

where $u(t)$ is a sequence of inputs and $y(t)$ is a sequence of outputs, with one input and one output for each time step. When the model has multiple inputs and multiple outputs (i.e. when there are several time steps), the variables will represent matrices. The order that the variables have in equations are therefore important.

When the mathematical model is known, it is possible to model the system as a function, analysing how the system behaves over time (Figure 2.5).

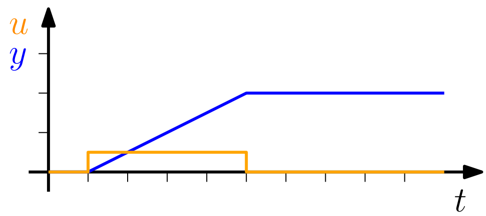

Figure 2.5: The output (blue line) and the input (orange line) as a function of time. Turning on the tap will cause the water level in the tank to rise, until the tap is turned off.

Humans experience time as a continuous succession of events. Usually, it is possible only to measure time steps, like in Figure 2.6. Functions and integrals are given in continuous time, but other calculations and computers require discrete variables. When the time steps get small, the discrete variables become good approximations of continuous time.

All of these models illustrate the same system but have different applications. Figure 2.2 is most illustrative and is easiest to understand. Figure 2.4 is a graphic representation of the interactions between signals and processes in the system. Eq. 2.1 is a mathematical representation that provides a language tool to formalise the science. Figure 2.5 illustrates the relationships between input and output over time. The models are tools to analyse the system, “to find the relationship between endogenous goals and the external environment” – Wiener (1985, 33).

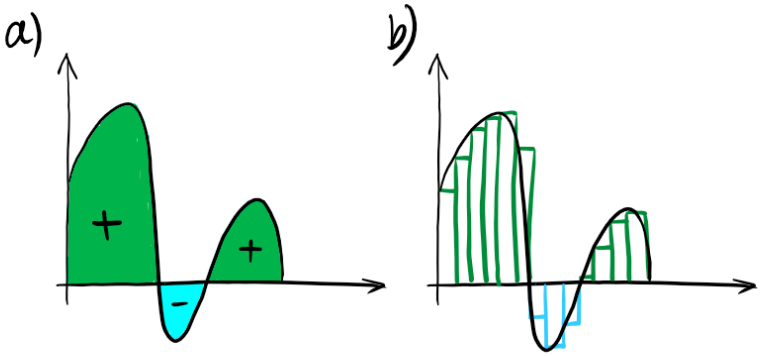

Figure 2.6: Whilst humans experience continuous time (a), computers measure snapshots of every time step (b). If the time step is very small, the discrete approximation is almost the same as the original. This is called the Riemann sum.

2.1.2 Linear, Time-Invariant System

Five statements of causality are assumed for the tank system.

1. The cause comes before the effect
2. The effect persists
3. Doubling the cause will double the effect
4. Solutions may be added together
5. The same effect will happen if the cause is initiated later.

According to the first statement, the tap must be turned before there is water in the tank. According to the second statement, the water is still in the tank in the next time step. This is clear from Figure 2.5. A hole in the tank would let the water out, but this will happen gradually (Figure 2.7), so the second statement still applies.

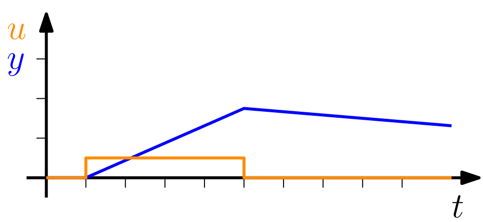

Figure 2.7: Time function of a leaking tank.

According to the third statement, doubling the cause will double the effect. By opening the tap to allow double water flow, there will be twice as much water in the tank, as illustrated in Figure 2.8.

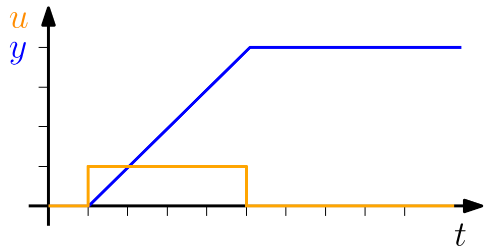

Figure 2.8: A tank system with double input will get double output.

Written formally as an equation, this may look like

$$y(t) = H(\alpha u) = \alpha H(u), \tag{2.2}$$

where α is the factor of how much the input is scaled. According to the fourth statement, solutions can be added together. If two taps are turned on at once, more water will appear in the tank as illustrated in Figure 2.9.

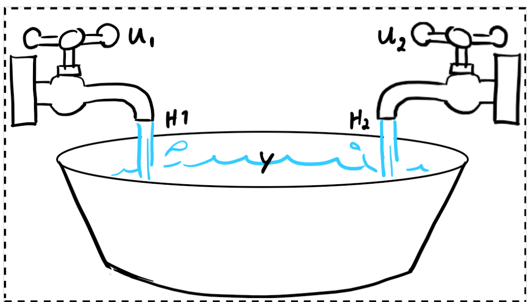

Figure 2.9: A tank system with two taps will accumulate more water.

This is illustrated in Figure 2.10a). The circle in the figure illustrates a summation point. The signals are positive by default, and negative signs are marked with a minus sign. Figure 2.10b) is thus equivalent of Figure 2.10a). Formally writing as an equation looks like

$$H(u_1 + u_2) = H(u_1) + H(u_2). \tag{2.3}$$

The assumptions eq. 2.2 and eq. 2.3 makes it possible to define H as linear.

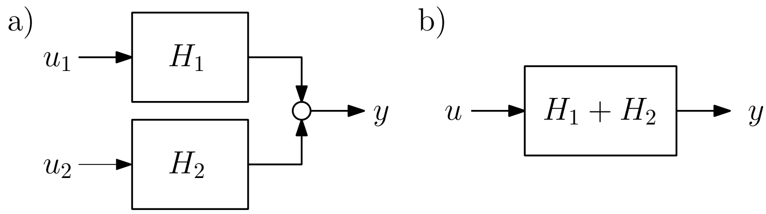

Figure 2.10: Two processes can be added.

According to the fifth statement, the same effect will occur if the cause is moved to another point in time. Figure 2.11 illustrates how the tank will fill up the same way if the tap is turned on now or later. Because the system behaves the same regardless of when it takes place, the system is time-invariant.

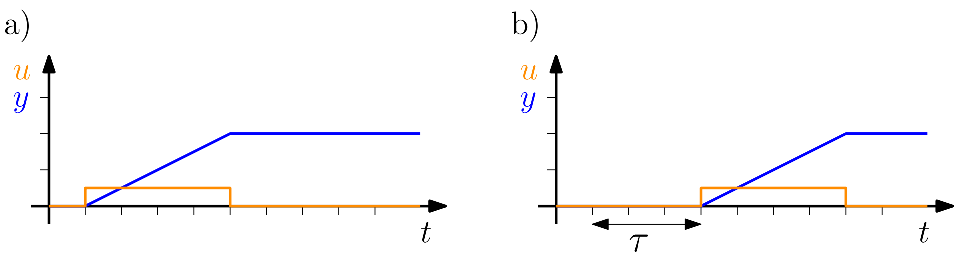

Figure 2.11: Moving the cause in time will have the same effect but at a later point in time.

A shift in time is mathematically modelled as $t+\tau$, and the following applies

$$y(t+\tau) = H(u(t+\tau)). \tag{2.4}$$

The system is now defined as linear and time-invariant (LTI), an important property in mathematical analyses of cybernetic systems. LTI systems may be described by simple and elegant mathematics, which is why non-LTI systems are often approximated to LTI systems.

In reality, no physical systems are completely LTI. The tank will fill twice as fast if the tap is opened twice as much, but only until the tank is full. When the water overflows, the system does not behave linearly anymore. However, it is usually interesting to analyse the tank system before it overflows, and then LTI properties apply.

Many systems behave LTI within a region, as illustrated in Figure 2.12. The system may thus be approximated to LTI. If the system is moving far from its working point, an approximation is no longer feasible.

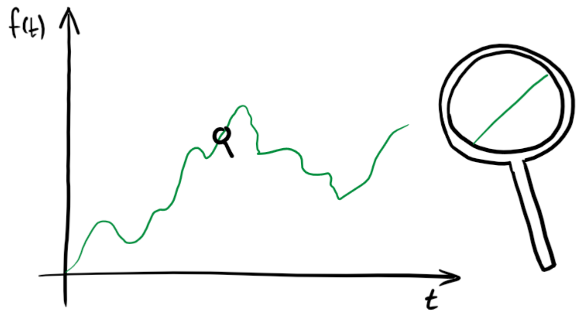

Figure 2.12: Most systems appear linear when looking closely.

2.1.3 Laplace Transform

The analysis thus far is done in the time domain, but LTI systems can be converted to the frequency domain with the help of the Laplace transform. The frequency domain allows for simpler and more elegant mathematics. But the calculations are abstract and hard to understand for newcomers to cybernetics. The Laplace transform may not make much sense if introduced without context as a prerequisite for learning engineering cybernetics. It may be beneficial to introduce the tool after the students have struggled with the more intuitive but less user-friendly mathematics of the time domain for a few weeks. The value of the Laplace transform may thus become apparent. The Laplace transform will not be derived here.

Whereas the time domain depends on the variable t, the frequency-domain depends on s. Time and frequency are reciprocal of each other, so when $t \to 0, s \to \infty$. s denotes differentiation, whilst $\frac{1}{s}$ denotes integration, which both are important effects in control, as will be elaborated in section 2.2.3.

2.2 System Analysis

Either the input, the process or the output is unknown in the system analysis. The unknown factor is the target for the mathematical analysis, as illustrated in Table 2.1 and can be determined from the past (green) or implemented into the future (red). The output, y, will be analysed in section 2.2.1 and the process (H) will be analysed in section 2.2.2. The input, also called the inverse problem, will be analysed in section 2.2.3 and 2.2.4.

Table 2.1: In system analysis, one of the three variables are always unknown. They can be determined from the past (green) and implemented into the future (red).

Unknown	Known	Operation
H	u, y	Identification
		Realisation
y	u, H	Postdiction
		Prediction
u	y, H	Estimation
		Control

2.2.1 Simulation

Simulation provides a way to analyse the output according to different inputs. Recalling the tank system described by

$$y(t) = H(u(t)). \tag{2.1}$$

If the aim is to fill the tank with five litres of water, and the input causes one litre of water to enter the tank per minute, the tank will be filled in five minutes. Mathematically describing the five minutes by using eq. 2.1:

$$y_1 = 1u_1 + 0u_2 + 0u_3 + 0u_4 + 0u_5, \tag{2.5a}$$

$$y_2 = 1u_1 + 1u_2 + 0u_3 + 0u_4 + 0u_5, \tag{2.5b}$$

$$y_3 = 1u_1 + 1u_2 + 1u_3 + 0u_4 + 0u_5, \tag{2.5c}$$

$$y_4 = 1u_1 + 1u_2 + 1u_3 + 1u_4 + 0u_5, \tag{2.5d}$$

$$y_5 = 1u_1 + 1u_2 + 1u_3 + 1u_4 + 1u_5, \tag{2.5e}$$

where the amount of water in the tank at each time step is the unknown factor. Observing eq. 2.5a, the last four values of H are zero. That is because the four last causes have not happened yet, and, according to the first statement from section 2.1.2, there are no corresponding effects yet.

According to the second statement, the effect persists. Thus, the litre added in the first time step is still present in eq. 2.5b–2.5e. In the second time step (2.5b), the input has caused another litre to be added to the tank. The one litre added in each time step persists down the column.

This tank example is trivial, chosen for illustrative purposes. But with more complex systems and many more time steps, it is more efficient to write the values in a table:

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix}}_{y} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}}_{H} \cdot \underbrace{\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix}}_{u} . \tag{2.6}$$

Because the signals and processes are functions of time and ordered in tables, it is crucial to write the variables in the mathematical equations in the correct order. Multiplying tables must be done from the rightmost side to the left, or the results may turn out wrong.

If the tank is leaking and water is dripping out, the 1 litre added would be reduced to 0.9 litres in the next time step, 0.81 in the next, etc., down the column, as in eq. 2.7, the effect fading over time. As the water will drip out faster with more pressure from more water, it will drip fast at first and slower as time goes by and the effect decreases.

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.9 & 1 & 0 & 0 & 0 \\ 0.81 & 0.9 & 1 & 0 & 0 \\ 0.73 & 0.81 & 0.9 & 1 & 0 \\ 0.66 & 0.73 & 0.81 & 0.9 & 1 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} . \tag{2.7}$$

There might already be water in the tank before the first cause is initiated. Eq. 2.1 is modified to include an initial value named b

$$y(t) = H(u(t)) + b(t). \tag{2.8}$$

The tank only has one state (i.e. water level), but another system may have two. An inverted pendulum, for example, has two states; speed and position. There is one initial value per state in the system, and the tank system has one initial value.

The water does not instantly appear one litre per minute in real life. In the physical world, it appears continuously over time. As was stated in Figure 2.6, it is more convenient to model with discrete variables. The unit of measurement for the input per time step is thus litre – u [litre].

The time step may be microseconds or hours, so it is inconvenient to have the input unit as litres. If the time step is tiny, the input will appear very small. Accordingly, the input may appear very large for large time steps. It is more convenient to measure the input per time to make the numbers easier to handle and comparable. It is thus desired to have the unit u [litre/time]. u [litre] is the equal to u [litre/time] multiplied with time step. The table in eq. 2.9 is modified to include a time step dt, together with an initial value of one litre of water:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} dt + \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}. \tag{2.9}$$

By observing the process matrices that have been stated in this chapter, some distinct characteristics appear. These are summarised in Figure 2.13.

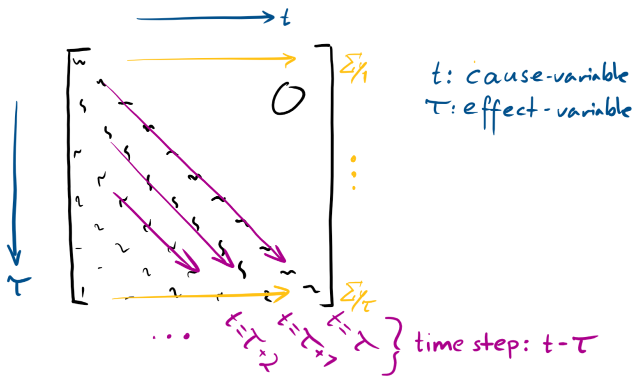

Figure 2.13: Characteristics of the H-matrix.

Because H relates outputs to inputs, the upper right triangle is always zero. t is called the cause-variable because a new cause is initiated every time step. τ is named the effect-variable because the persistent effect of the causes is displayed down the columns. In the diagonal where $t = \tau$, the cause and effect relationship is most apparent. Turning on the tap for one minute causes one litre of water to be added to the tank. The diagonal below illustrates the effects of the cause one time step later ($t = \tau + 1$), and the diagonal two steps below illustrates effects after two time steps ($t = \tau + 2$), etc. In eq. 2.9 the effect persists and will always be one litre but in eq. 2.7 the water is dripping out, and the effect is fading.

The amount of water (y) in the tank at each time step is found by summing the values in the respective rows and adding the initial value. To be able to sum the values, they must be stated in discrete time. To emphasise the difference t and τ are used in continuous time, and i and j respectively are used in discrete time. The water level at the fifth time step can therefore be calculated by

$$y_5 = \sum_{i=1}^{5} H_{i5} u_i dt + b_5. \tag{2.10}$$

Generalising to apply to all outputs by writing:

$$y_j = \sum_{i=1}^{j} H_{ij} u_i dt + b_j, \tag{2.11}$$

which corresponds to a Riemann sum that was explained in Figure 2.6. Making the time steps of the summation small and summing the values is how integrals are calculated. In the tank system example, the time-step could be decreased to one second instead of one minute. 2.11 can thus be written as

$$y_5 = \int_{t=1}^{5} H(t,\tau) u(\tau) d\tau. \tag{2.12}$$

Observe that an integral uses continuous time. Thus the variables t and τ are again adopted. Including initial conditions, the general equation becomes

$$y(t) = \int_{0}^{t} H(t-\tau) u(\tau) d\tau + b(t), \tag{2.13}$$

which is a general way to describe the system. This equation is much used in engineering cybernetics.

The analysis so far is done on operator form, i.e. H is an operator that converts the input function to an output function. Another way to describe the system is in recursive form

$$y_1 = y_0 + u_1, \tag{2.14a}$$

where the output in the current time step is the output from the previous time step plus the input in the current time step. This operation can be done indefinitely

$$y_2 = y_1 + u_2, \tag{2.14b}$$

$$y_3 = y_2 + u_3, \tag{2.14c}$$

$$y_{n+1} = y_n + u_{n+1}, \tag{2.14d}$$

where eq. 2.14d is much more compact than, e.g. a matrix of a thousand time steps.

Without going into further detail on recursive form, the output can be simulated by using eq. 2.11, eq. 2.14d or simply multiplying the H matrix directly. Simulation may be used as postdiction to understand what went wrong in Figure 2.14, or it may be used as a prediction to prevent the situation in Figure 2.14. Simulation may also be used to check if the system has the desired behaviour and monitor the system's behaviour for weather, wear and tear.

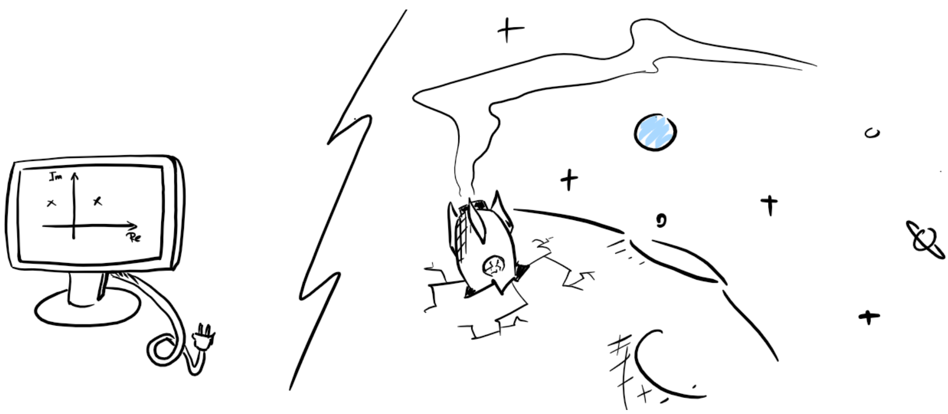

Figure 2.14: Simulation monitors the output of the system to various inputs. A pole in the right half of the frequency plane causes the system to be unstable.

By simulating the output for every possible input, finding which input gives the right output is possible. Simulation is often performed through computers, and knowledge within information and communication technology (ICT) is crucial for cybernetics engineers.

2.2.2 Process Identification

The previous section showed how the process could be modelled as a matrix (see, e.g. eq. 2.9), with every time step adding a new dimension to the matrix. Matrices take up much space, so it is more convenient to model it as a function. Figure 2.15 shows some essential variables.

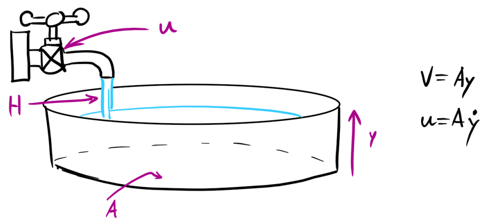

Figure 2.15: Modelling the volume of the tank.

From the figure, the volume flow into the tank is derived to be

$$A\dot{y} = u, \tag{2.15}$$

which is a differential equation describing the tank. For LTI systems, it is possible to model the process as a transfer function. The transfer function models the system's output for every possible input and disregards initial conditions. It is not always possible to find H, as there does not always exist a process that can transfer the input to the output. For the tank, the Laplace transform of the differential equation is

$$sAY = U \tag{2.16}$$

solving for the output-input ratio

$$\frac{Y}{U} = \frac{1}{sA} \tag{2.17a}$$

$$H = \frac{1}{sA}. \tag{2.17b}$$

The process of the tank system is now identified and may be realised into a physical system.

Another LTI system approximation is a cruise controller of a car. Figure 2.16 illustrates the car modelled as a mass and damper system (left) and as a free body diagram (right).

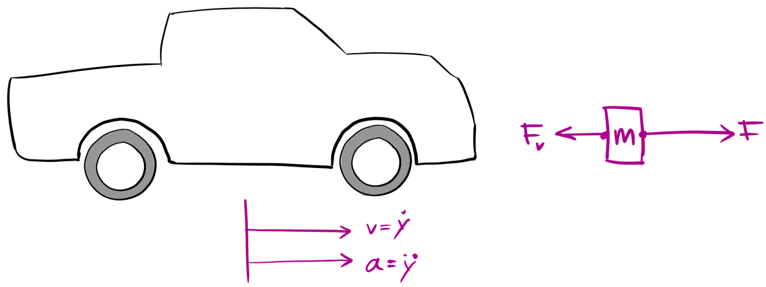

Figure 2.16: Illustration and free body diagram of car.

Using the free body diagram and Newton's second law:

$$\sum F = ma, \tag{2.18}$$

where the total force is made up of the force driving the car forwards and the dampening and friction forces working in the opposite direction:

$$F - F_d = ma, \tag{2.19}$$

where F_d is the dampening coefficient d multiplied by velocity, and F is the input. The displacement is given by y, the velocity is the displacement differentiated with respect to time, $\dot{y}$, and acceleration is velocity differentiated with respect to time, $\ddot{y}$. The differential equation describing the system is thus

$$u - d\dot{y} = m\ddot{y}. \tag{2.20}$$

Disregarding the zero initial conditions, the Laplace transformed becomes

$$\frac{U}{s} - dsY = ms^2Y. \tag{2.21}$$

The transfer function is thus

$$\frac{U}{Y} = \frac{1}{ms+d}, \tag{2.22a}$$

$$H = \frac{1}{ms+d}. \tag{2.22b}$$

2.2.3 Control in the Time Domain

As was stated in the introduction to this chapter, the main goal of engineering cybernetics is to predict which causes may lead the system to a specific outcome in the future (red circle in Figure 2.17). This outcome is reached by controlling which choices are most likely to lead to the goal (red path). Due to disturbances and noise, there might occur a deviation from the desired path (yellow).

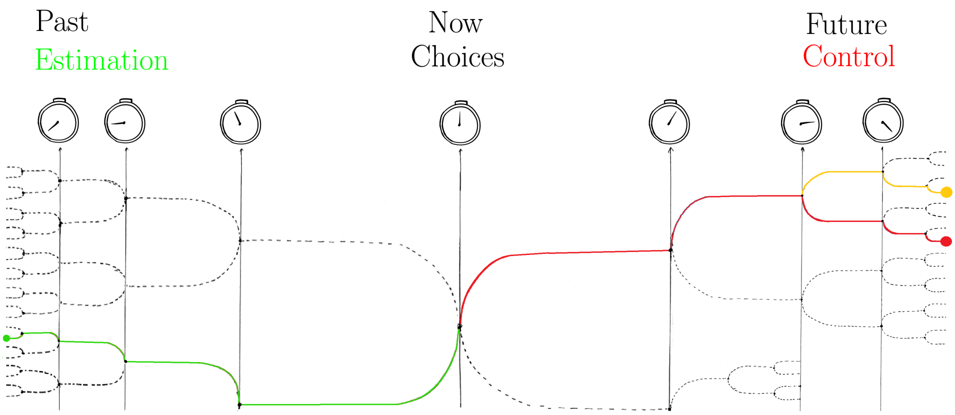

Figure 2.17: Engineering cybernetics may be used to estimate the events from the past (green) or to control the future events (red). If a deviation (yellow) occurs, it is possible to reconsider the causes.

Another aspect of the science is estimation. An effect is presented, and engineering cybernetics is used to estimate which causes (green in Figure 2.17) that made the effect come about. The principle of cybernetics is central in both estimation and control, with one difference. The cause of control lies in the future, whereas the cause of estimation lies in the past. This section is concerned with control.

Section 2.2.1 showed that the desired output could be obtained by trying every possible input, observing which produces a satisfactory output. Another way is to state the desired output and calculate what the input needs to be. A controller is used to achieve the desired behaviour of the system.

Controllers usually get the system to the reference by use of proportional (P) effect, integral (I) effect, derivative (D) effect or a combination of these. Usual practice is to find the correct controller is by trial and error. By modelling the system around desired requirements, the suitable controller may automatically appear by inverting the trial and error process.

The problem is the cause and effect chain of the tank. Turning on the tap (u) causes a process of water pouring in (H) and leads to the effect: a tank full of water (y). Recalling the mathematical representation of the system in eq. 2.1, t is now omitted in the calculations to read

$$y = Hu. \tag{2.23}$$

Denoting the intended outcome of the system to be a reference r. The following output is desired:

$$y = r \tag{2.24}$$

The naive solution is to multiply H with its inverse, creating the identity matrix. A block is added in Figure 2.18.

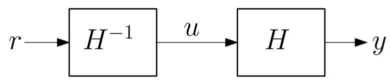

Figure 2.18: The inverted H is added, so the output is equal to the reference.

The reference is the signal into to H^{-1}, and the input is the signal into H. The mathematical representation of the input is now

$$u = H^{-1}r. \tag{2.25}$$

Because processes are functions of their input signals, the effect of adding another block is that the blocks are multiplied together. The same effect is found by substituting eq. 2.25 into eq. 2.23 to become

$$y = H^{-1}Hr, \tag{2.26a}$$

$$y = r, \tag{2.24}$$

which is the intended outcome. However, this solution is naive as there may be values of r that are not possible to obtain through H. While this exists in some cases (i.e. in minimum phase systems), it is not common. The trouble manifests in non-singular matrices that are not invertible. The tank is an example of such. Setting the reference in the tank system to five litres of water requires H to instantly fill the tank with five litres, which is impossible since the input must be very large or even infinite.

The adjusted solution is to make a modified r that gradually increases from zero to five litres of water. Whilst r is an ideal outcome, the following is a reasonable outcome

$$r' = Tr. \tag{2.27}$$

T is a filter that over time changes value from zero to one, thus obtaining the necessary effect. In the block diagram, it will look like Figure 2.19.

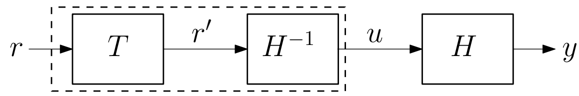

Figure 2.19: A filter is added to so the intended outcome is reasonable. The dashed boundaries around T and H^{-1} illustrates that they in the real world cannot be separate.

According to the block diagram, the input is now

$$u = H^{-1}r' \tag{2.25}$$

$$Hu = r'. \tag{2.28a}$$

Substituting eq. 2.28a into eq. 2.27

$$Hu = Tr, \tag{2.29a}$$

$$u = H^{-1}Tr. \tag{2.29b}$$

Note that $H^{-1}T$ may exist even if H^{-1} is not possible. Substituting eq. 2.29b into eq. 2.23 becomes

$$y = Tr, \tag{2.30}$$

which is a reasonable outcome when T approaches one.

The equations can also be found by reducing the block diagram directly. Blocks connected by a signal may be multiplied together, creating a new block. Multiplying the process with its inverse produces the identity, which virtually disappears. The result is shown in Figure 2.20.

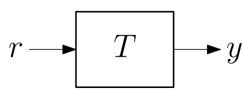

Figure 2.20: $H^{-1}H$ equals to the identity, which virtually disappears as the filter dominates the system.

Deriving the equation directly from the block diagram gives the same result as in eq. 2.30.

The complication is that unknown causes may influence the system, as illustrated in Figure 2.21.

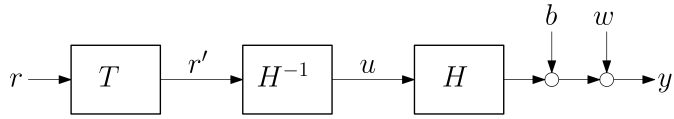

Figure 2.21: Known (b) and unknown (w) influences on the system.

Known initial conditions (b) and unknown disturbances or model errors (w) usually work on the system. The equation corresponding to the block diagram is

$$y = Hu + b + w. \tag{2.31}$$

The special case is when there are no unknown influences on the system, as illustrated in Figure 2.22. There is only a known amount of water in the tank before the first cause.

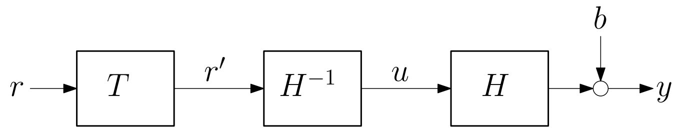

Figure 2.22: Special case: there are no unknown influences on the system.

If there is already one litre of water in the tank, the process will cause the total amount to become six litres, even though the reference is five litres. Mathematically described, it will look like

$$y = Hu + b. \tag{2.32}$$

The process only needs to fill four litres if there is already one litre of water in the tank. The initial conditions are counteracted by subtracting b at the start. The block diagram is illustrated in Figure 2.23.

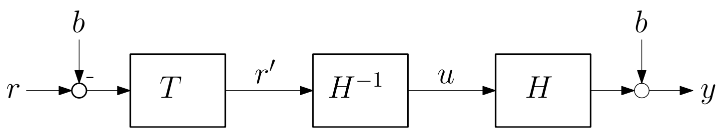

Figure 2.23: b is subtracted from the reference.

The figure shows that r' has been adjusted from eq. 2.27 to become

$$r' = T(r - b). \tag{2.33}$$

By observing the diagram, the input may now be described by

$$u = H^{-1}T(r - b), \tag{2.34a}$$

$$Hu = T(r - b). \tag{2.34b}$$

Substituting with Equation 2.32, the output is

$$y = T(r - b) + b, \tag{2.35a}$$

$$y = Tr + (I - T)b. \tag{2.35b}$$

Defining

$$S = I - T, \tag{2.36}$$

where I is the identity and S is the sensitivity function. The equation shows a trade-off between T and S, and the two may never be zero at the same time. Eq. 2.35b may thus be written

$$y = Tr + Sb, \tag{2.37}$$

which is a satisfactory result as long as $T \to 1$ and $S \to 0$. The calculations are often more complicated, however.

The normal case is that unknown influences cause deviations to the system, as in Figure 2.24. w may represent model imperfections or external disturbances like rain, wind, leaks, etc.

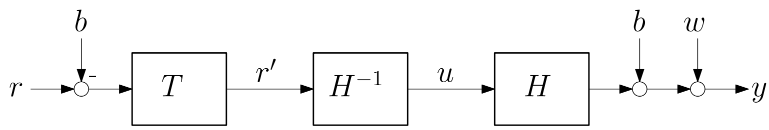

Figure 2.24: Unknown influences are usually part of a system.

According to the figure, the output may be described as

$$y = Hu + b + w. \tag{2.31}$$

b is counteracted like before

$$Hu = T(r - b). \tag{2.34b}$$

Substituting 2.34b and 2.31 and making use of eq. 2.36:

$$y = T(r - b) + b + w, \tag{2.38a}$$

$$y = Tr + Sb + w. \tag{2.38b}$$

When $T \to 1$, then $S \to 0$, and

$$y \approx r + w. \tag{2.39}$$

The equation shows that w has a real influence on the system's output. This influence must be counteracted.

Error estimation is necessary to remove the influence from w. Figure 2.25 illustrates how it can be done.

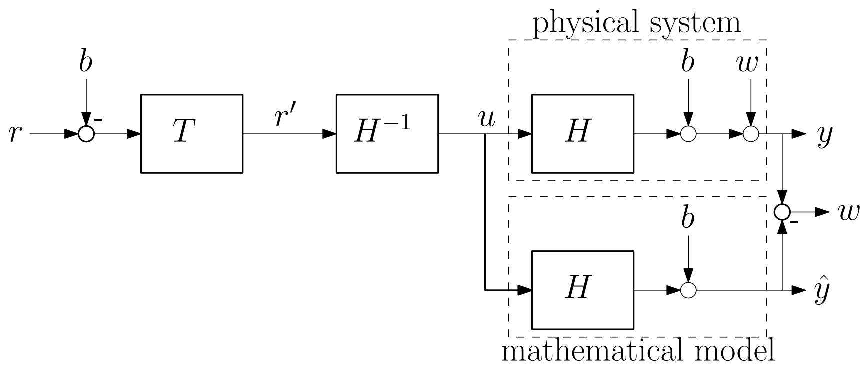

Figure 2.25: w is estimated by subtracting the estimated output from actual output.

$\hat{y}$ is the estimated output from the mathematical model. This was already calculated in eq. 2.37. Only the external influences are assumed to differ between the mathematical model and the physical plant (eq. 2.38b), so

$$y - \hat{y} = w \tag{2.40a}$$

$$Tr + Sb + w - (Tr + Sb) = w \tag{2.40b}$$

Feedback is introduced to compensate for w. Just like b, w must be subtracted from the reference at the start. As w always depends on the output of the system, it is permanently fed back to the start, creating a closed-loop system, as illustrated in Figure 2.26.

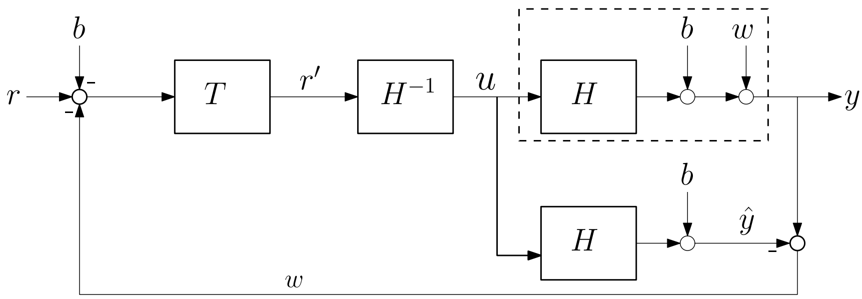

Figure 2.26: w is fed back as an input to the system.

Feeding the output back as an input may eliminate the influence from disturbances and noise that is not accounted for in the model. Feedback is a necessary prerequisite for simplifying the physical world to a model. Closed-looped models, therefore, have a central part in engineering cybernetics.

According to the diagram, the adjusted reference is now

$$r' = T(r - b - w). \tag{2.41}$$

The modified reference is still described by

$$Hu = r'. \tag{2.25}$$

Substituting eq. 2.41 and eq. 2.25 to

$$Hu = T(r - b - w), \tag{2.42}$$

and substituting this equation into eq. 2.31, and taking eq. 2.36 into account, the output may be described

$$y = T(r - b - w) + b + w, \tag{2.43a}$$

$$y = Tr + Sb + Sw, \tag{2.43b}$$

$$y = Tr + S(b + w). \tag{2.43c}$$

When $T \to 1$, then $S \to 0$, and

$$y \approx r, \tag{2.44}$$

which is the intended outcome.

Example of feedback in a real-life setting is shooting a bow and arrow. Figure 2.27 illustrates a person that aimed for the bull's eye, but the arrow hit over. When aiming anew, they adjust the reference downwards.

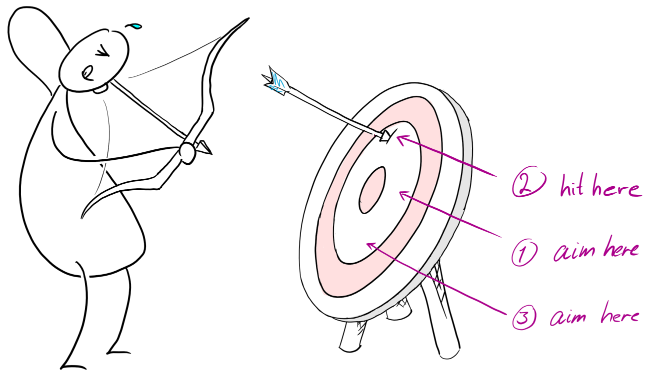

Figure 2.27: Aiming at (1) causes the arrow to hit the target in (2). Observing the error, the second arrow is aimed at (3).

Block diagram manipulation is useful to simplify the model. Whilst Figure 2.26 is descriptive, it has a lot of excess information.

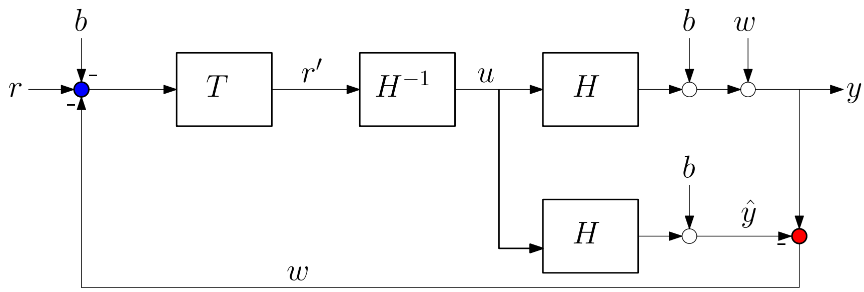

Figure 2.28: The diagram is easy to understand but impractical.

The red summation has been moved along the feedback line to the blue summation point in Figure 2.29. This operation is allowed because the order of addition and subtraction does not matter, even in matrices.

As the two summation points are added to one, the two negative signs assigned to $\hat{y}$ become one positive sign. w virtually disappears, and b cancels out. The red summation point is moved one step further in Figure 2.30.

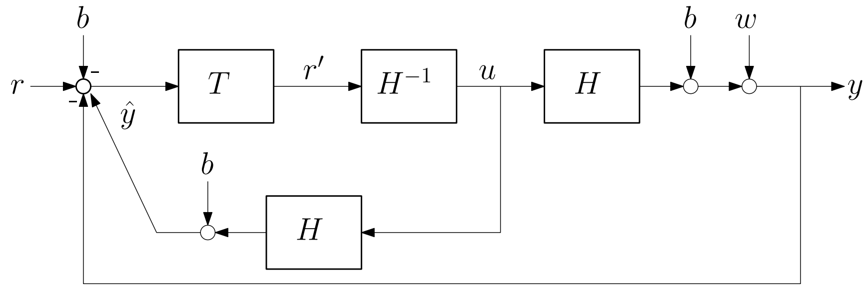

Figure 2.29: The red summation is moved to the blue summation and become one.

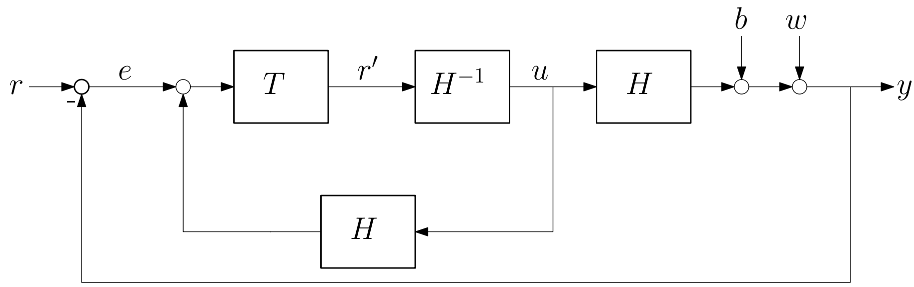

Figure 2.30: The red summation is moved one more step. b is eliminated.

A new variable is introduced in the last figure: the error e between the desired output and actual output

$$e = r - y. \tag{2.45}$$

According to the block diagram, the adjusted reference is now

$$r' = T(e + Hu). \tag{2.46}$$

Substituting into eq. 2.25 and solving for u

$$u = H^{-1}T(e + Hu), \tag{2.47a}$$

$$Hu = T(e + Hu), \tag{2.47b}$$

$$(I - T)Hu = Te, \tag{2.47c}$$

$$u = H^{-1}(I - T)^{-1}Te. \tag{2.47d}$$

In Figure 2.30, everything left of H is the controller that gets the system to its desired output. Those processes may be collected in on controller block K, as is done in Figure 2.31.

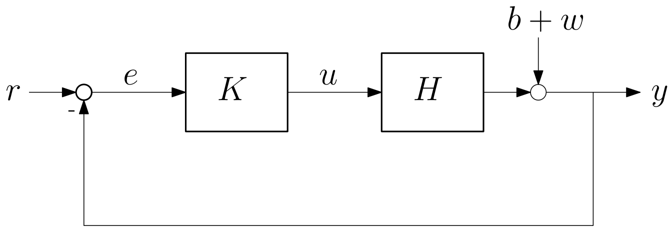

Figure 2.31: The subsystem that make up the controller is reduced to one single block named K.

The block diagram in Figure 2.28 is easy to understand but large and unpractical. It is reduced to Figure 2.31 which is more elegant and practical but harder to understand. Corresponding to the latter, eq. 2.47d may thus be written as

$$u = Ke, \tag{2.48a}$$

where

$$K = H^{-1}(I - T)^{-1}T, \tag{2.48b}$$

$$T = HK(I + HK)^{-1}. \tag{2.48c}$$

Thus, a general controller equation is derived. The controller for a specific process is found by substituting relevant filters (T) and processes (H) into the equation.

2.2.4 Control in the Frequency Domain

The controller may also be found in the frequency domain.

The problem is the cause and effect chain of the cruise controller in Figure 2.16. It may be mathematically modelled as

$$y = Hu. \tag{2.23}$$

u is still the input signal, y is the output signal, and H is the process that connects the two. Recall that the process was stated to be

$$H = \frac{1}{ms + d}, \tag{2.22b}$$

where m is the mass of the car, and d is dampening from drag and friction. The car starts with the speed of 0 km/h, and the intended outcome is 80 km/h, as illustrated in Figure 2.32.

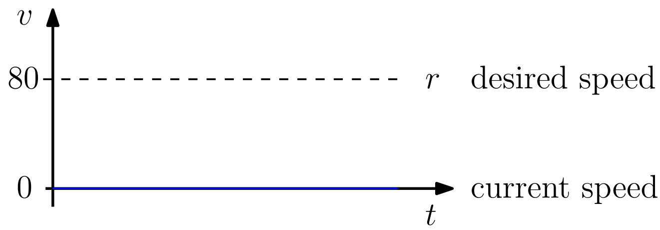

Figure 2.32: Desired speed (r) and current speed (y). A controller may get the system to the reference.

The naive solution is to implement an inverted H first. Figure 2.33 shows how the car them is required to instantly go from 0 to 80 km/h at $t = 0$, which is impossible.

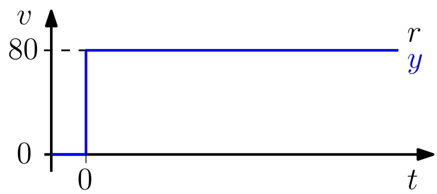

Figure 2.33: There is no process that instantly can bring the car from 0 km/h to 80 km/h.

The inverse of eq. 2.22b is

$$H^{-1} = ms + d. \tag{2.49}$$

The introduction of this chapter stated how $s \to \infty$ when $t \to 0$. The reason is that s is a differentiator. When the system is given infinite time to obtain the reference, the differentiated s will approach zero. When the system is given zero time to obtain the reference, the differentiated will approach infinity, i.e. infinite acceleration is needed to obtain the reference instantly. When s is infinitely large, H^{-1} must be infinitely large according to eq. 2.49, which is impossible. The mathematics agree that there is no H that instantly can bring the system from 0 km/h to 80 km/h.

The adjusted solution is to introduce a modified reference. The effect is illustrated in Figure 2.34.

The modified reference is still described by

$$r' = Tr. \tag{2.27}$$

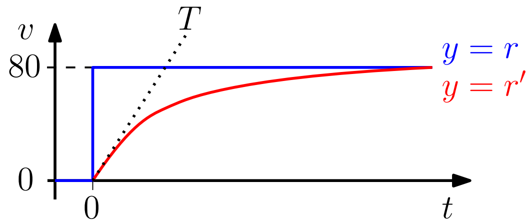

Figure 2.34: A filter T is introduced to gradually increase the reference from 0 to 80 km/h.

The input is described by

$$u = H^{-1}Tr. \tag{2.29b}$$

Assuming that T is still a low pass filter, the equivalent in the frequency domain will be

$$\underbrace{T}_{\text{time domain}} \Leftrightarrow \underbrace{\frac{1}{Ts+1}}_{\text{frequency domain}}. \tag{2.50}$$

The modified reference will, according to eq. 2.27 and the figure, be

$$r' = \frac{1}{Ts+1}r, \tag{2.51}$$

which is well defined, as $s \to 0$ when $t \to \infty$, causing $r' \to r$. Substituting eq. 2.49 and eq. 2.50 into eq. 2.29b gives

$$u = \frac{ms+d}{Ts+1}r. \tag{2.52}$$

Substituting eq. 2.52 with eq. 2.29b gives

$$H^{-1}T = \frac{ms+d}{Ts+1}, \tag{2.53}$$

which is defined for all s and also stable. According to eq. 2.23, the output is therefore given by

$$y = \frac{1}{Ts+1}r, \tag{2.54}$$

which according to eq. 2.51 is equal to the modified reference, and the intended outcome is achieved.

The classical controller is to be found. In the time domain, the controller was derived to be

$$K = H^{-1}(I - T)^{-1}T. \tag{2.48b}$$

Substituting with eq. 2.49 and eq. 2.50 and solving for K gives

$$K = (ms + d)\frac{1}{1 - \frac{1}{Ts+1}}\frac{1}{Ts + 1}, \tag{2.55a}$$

$$K = \frac{ms + d}{Ts}, \tag{2.55b}$$

$$K = \frac{m}{T} + \frac{d}{Ts}, \tag{2.55c}$$

where the constant denotes a proportional gain and s in the denominator is an integrator. Thus the integrator gain is

$$K = K_P + \frac{K_I}{s}, \tag{2.56a}$$

$$K_P \overset{\text{def}}{=} \frac{m}{T}, \tag{2.56b}$$

$$K_I \overset{\text{def}}{=} \frac{d}{T}, \tag{2.56c}$$

which means that a PI-controller is needed for the cruise controller to achieve and maintain the desired speed. It is possible to check if the calculations are correct by using eq. 2.43c again

$$y = Tr + S(b + w), \tag{2.43c}$$

where

$$T = \frac{1}{Ts + 1}, \tag{2.50}$$

and $S = I - T$, so

$$S = \frac{Ts}{Ts + 1}. \tag{2.57}$$

If $T \to 1$ and $S \to 0$, then $y \to r$, which is desirable. Thus the controller works.

Finding the controller needed for the water tank has the same approach. The controller equation is

$$K = H^{-1}(I - T)^{-1}T. \tag{2.48b}$$

A low pass filter is implemented

$$T = \frac{1}{Ts + 1}. \tag{2.50}$$

The process of the tank is

$$H = \frac{1}{sA}. \tag{2.17b}$$

Substituting eg. 2.50 and eq. 2.17b into eq. 2.48b and solving for K

$$K = \frac{sA}{1 - \frac{1}{Ts+1}} \frac{1}{Ts + 1}, \tag{2.58a}$$

$$K = \frac{sA}{Ts}, \tag{2.58b}$$

$$K = \frac{A}{T}, \tag{2.58c}$$

which is the proportional gain. This shows that a P-controller is sufficient to fill a tank with the desired level of water.

Recognising patterns is important when modelling systems. The same approach is used in both the cruise controller example and the water tank example. The same approach was used in both the time domain and the frequency domain. Because both systems abide by cybernetic principles, they may be described by similar mathematical equations. The process will differ between examples, and the filters may be different, but the same patterns are generally used when modelling physical systems. Recognising these patterns and applying them to new systems is far more valuable than memorising formulas and recipes.

One low pass filter is used for each of the examples presented here. That is because the desired output was speed and water level, respectively. For a process like stabilising an inverted pendulum, two low pass filters are necessary. That is because an inverted pendulum has two states and because both position and velocity must be controlled.

The controller is built by establishing where the system is and where it needs to be. A recipe on how to work out the controller is formulated to be

1. Establish the system boundaries and the desired output.
2. Try to inverse the cause and effect chain directly.
3. If that does not work, ask for something more reasonable.
4. Recognise that the model is not perfect. Find error by comparing model and measurement.
5. Subtract the measured deviation from what you ask for.
6. The controller appears.

This approach may be applied to any system. The same basic approach can be used when modelling a control system: a water tank, a cruise controller, or something completely different. Even in vastly different systems, the procedure is similar because they follow the cybernetic principles.

The usual practice after establishing the system boundaries, is to guess a controller and implement, observing whether the effects are satisfying. This approach might be intuitive for experienced engineers, but for newcomers, this kind of guesswork may obstruct the learning process as it promotes memorising and cramming. The usual practice may start with the equation

$$T = HK(I + HK)^{-1}, \tag{2.48c}$$

where the process for the cruise controller is given by

$$H = \frac{1}{ms + d}. \tag{2.22b}$$

A P-controller is given by

$$K = K_P. \tag{2.59}$$

Substituting eq. 2.22b and eq. 2.59 into eq. 2.48c

$$T = \frac{K_P}{ms + d} \frac{1}{1 + \frac{K_P}{ms+d}}, \tag{2.60a}$$

$$T = \frac{K_P}{ms + (d + K_P)}. \tag{2.60b}$$

As $t \to \infty$ (steady state), $s \to 0$ and the filter becomes

$$T = \frac{K_P}{d + K_P}. \tag{2.61}$$

Recall that $r' = Tr$, according to eq. 2.27. Because the dampening is not zero in real systems, the filter will not approach one, and the reference will not be obtained. A P-controller is thus not satisfactory for a cruise controller in a car. The actual output might look like in Figure 2.35.

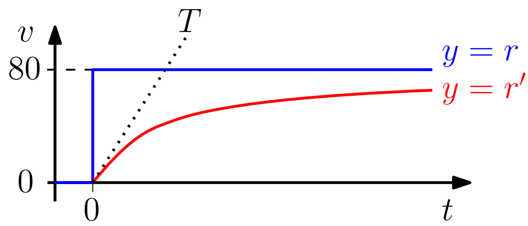

Figure 2.35: A standard deviation will occur if a P-controller is implemented.

Using the same method with a PI-controller will lead to the equation

$$T = \frac{sK_P + K_I}{ms^2 + s(d + K_P) + K_I}, \tag{2.62}$$

which, as $t \to \infty$ will become

$$T = \frac{K_I}{K_I} \tag{2.63}$$

which is the identity, and according to $r' = Tr$ in eq. 2.27 the intended output will then be reached. Using the same method and implementing a P-controller in the water tank system will lead to

$$T = \frac{K_P}{sA + K_P}. \tag{2.64}$$

$T \to 1$ as $s \to 0$, and the system will obtain the desired output. As was concluded earlier, a P-controller is sufficient for obtaining the desired water level in a tank.

This "usual practice" method is faster than the approach introduced first and is therefore preferred by engineers who have developed intuition about cybernetic principles. However, it may confuse newcomers to cybernetics who do not have this intuition yet. It may be better if students are taught the intuitive alternative first and are introduced to the "usual practice" when they have developed some intuition.

2.3 A Philosophical Approach to Cybernetics

The approach to explaining cybernetics has until now been of mathematical nature. But science does not have all the answers. The intro to this chapter stated how engineers, scientists and philosophers have all contributed to technological development. Ethical questions, such as determining human values, right or wrong, are of a philosophical nature. Despite philosophy and science having tight historical links, philosophy is often viewed as separate or antagonistic to science (Laplane et al. 2019). But as Albert Einstein stated in correspondence to Robert Thornton (1944),

> A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is – in my opinion – the mark of distinction between a mere artisan or specialist and a real seeker after truth.

As this chapter aims to propose a way to establish cybernetic intuition, the remainder of the chapter will be devoted to the philosophical aspects of cybernetics.

2.3.1 Thoughts, Mathematics and Physical World

If a child is given a rake and told to gather the leaves from the lawn, they will probably at some point place the rake in their palm, trying to balance it upright. The child does it out of curiosity or boredom, ignorant that this is a complex control system called an inverted pendulum, a famous example within cybernetics of an unstable system that becomes stable after adding a controller. Simply placing the rake in the palm will result in it falling. But when the eyes send information to the brain, which processes the data and commands the hands to move this way or that, the rake might stay upright. The eyes are sensors that feed the output back as an input in a closed-loop system, the brain is the controller, and the hands are the actuators that apply a force to the rake. (Brajkovic 2020)

Without having any knowledge of what a controller is, the child instinctively knows what to do. Control is at play when they fill a tank with five litres of water, and later when they grow up as they learn how to drive and in countless other conscious and unconscious situations throughout life. The brain performs extraordinary calculations every day. The challenge is to become aware of it and to translate the knowledge to mathematics. (Brajkovic 2020)

Even a child will know that a ball will move faster if kicked harder. The child knows this because they have experienced it in the physical world. According to Newton's second law, this is also true. These three, physical existence, thoughts and mathematics, are connected. Popper (1978) and Penrose (2004) have described the connection as a triangle. Penrose's triangle is reproduced in Figure 2.36.

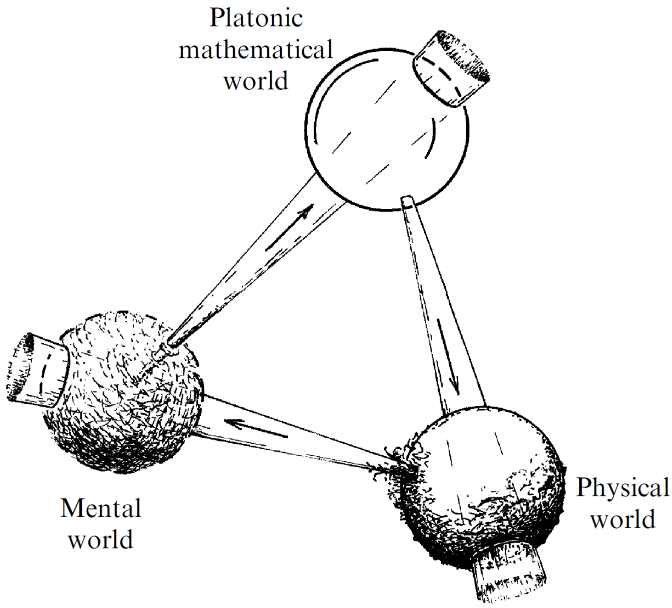

Figure 2.36: Three worlds of Penrose (2004, p. 20), relaxed scheme.

The triangle illustrates the connection between physical existence, mental perception and mathematics. The child has observed on multiple occasions that the ball moves faster when kicked harder. That does not mean that they know everything from the physical world. Some things may be lost in translation and lead to misconceptions. The child may also imagine kicking the ball to space, even though they know it is impossible in the physical world.

Similarly, mathematics might be described by mental perception, and mathematics may describe the physical world. Transforming intuitive mental knowledge to mathematics may prove that the ball moves faster when kicked harder. Using the same mathematics, other principles that are less intuitive may also be derived. Thus, mathematical proof lays the foundation stone to understand deeper universal order and to science itself.

Popper and Penrose's views have one distinct difference regarding mathematics. Whilst the first world contains all material things and the second world contains thoughts and feelings, their view on the mathematical world differs. Popper (1978) describes the third world as the world of human constructs, i.e. the world of music, languages, sculptures, cars and mathematics, thus making the first and the third world somewhat overlapping. Penrose (2004) has the view of mathematical Platonism, claiming that mathematics was not invented by humans but is an absolute truth that is merely discovered.

This discussion on whether mathematics is a human construct or an absolute truth split scholars in two. Despite differences in opinion on this subject, engineers, physicists and mathematicians all manage to perform their work by relying on mathematical principles. Mathematics provides a convenient tool that complements mental perception and the physical world. Penrose's triangle is thus modified to suit the practical needs of engineers in Figure 2.37: getting an idea, transforming it to mathematics, implementing physically and checking if it fits with the idea.

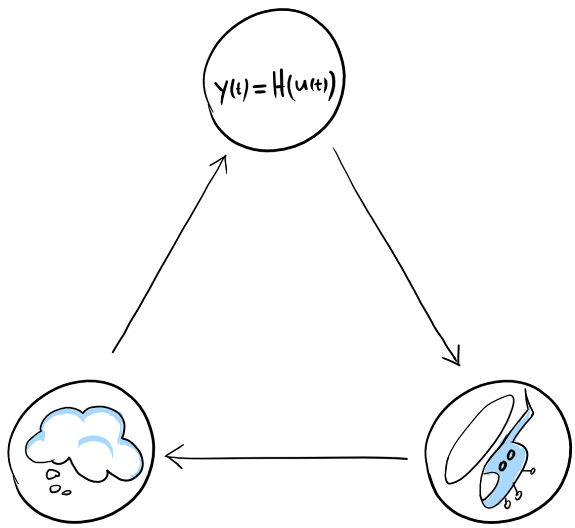

Figure 2.37: The engineering working triangle: getting an idea, transforming it to mathematics, implementing physically and checking if it fits with the idea, etc.

2.3.2 Time and Causality

The transition between physical and mental truth can be tricky. Time and causality are two principles that seem to exist in the physical world and are recognised by the human mind until we try to explain what they are.

The human mind orders events into what has been, what is, and what may come to be. This indefinite continued progress of existence is called time. Whilst humans experience time as continuous, it is illustrated as snapshots in a film strip in Figure 2.38.

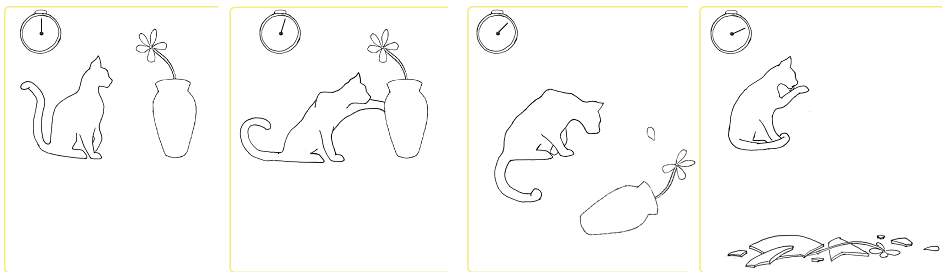

Figure 2.38: Time is the irreversible succession of choices, actions and events that brings future events through the present and into the past.

The four snapshots in Figure 2.38 illustrate four instances of now in rapid succession. Another way to illustrate it is provided in Figure 2.39. The present is where choices, actions and events are happening. Once a choice is made, it becomes part of one single past and cannot be changed.

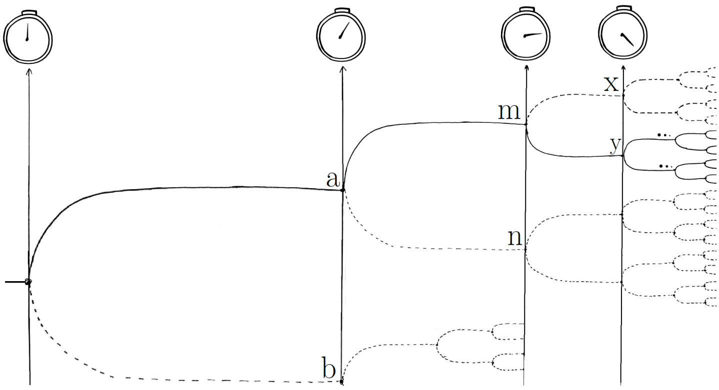

Figure 2.39: Simplified choice tree where (a) the cat lifts the paw to touch the vase; (m) the cat observes the vase fall; (y) the cat licks the paw.

A question arises when exploring time. How do we know that time moves forward? The vase starts in a position of chaos on the floor in Figure 2.40, before it jumps into the air to a state of higher order, causing the cat to catch it with its paw. While this seems intuitively impossible for the human brain, it also contradicts the second law of thermodynamics; a system will move to a state of greater chaos.

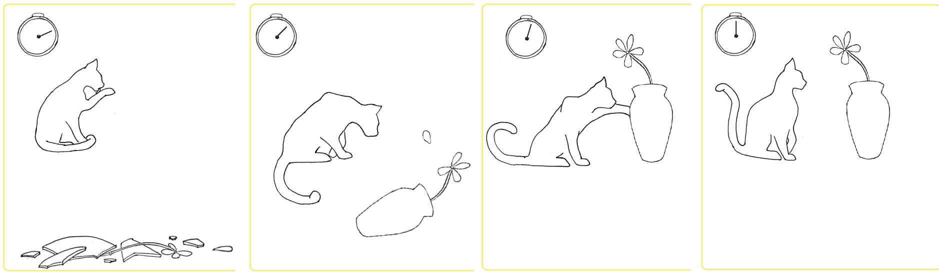

Figure 2.40: Time moving backwards violates the second law of thermodynamics, that a system will move to a state of greater chaos.

Back to Figure 2.39. The choices made in the first snapshot lead to the choices that are made now, leading to choices in the third snapshot. When a choice, action, or event made in the present is partly responsible for choices, action, or events in the future, causality is at play. The cat causes the vase to shatter to the floor in a cause and effect relationship.

Philosophers disagree on whether time leads to causality or the other way around or if they are simply constructs of the human mind. This chapter appeals to human intuition, where both time and causality appears real and are significant parts of our lives, and further discussion on the realness of time and causality will not be made.

2.3.3 Cybernetics

Causes lead to effects, but many actions are initiated to obtain a desired outcome. An example is illustrated in Figure 2.41, where it is assumed that the cat pushes the vase to break it, not because it is curious about the effect.

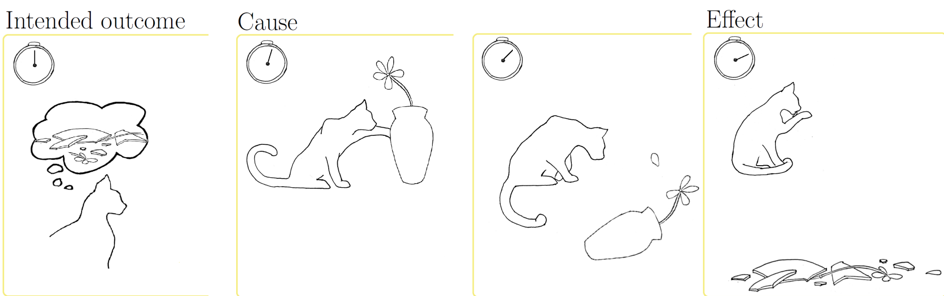

Figure 2.41: Cybernetics is the study of cause and effect and how the principle may be inverted to obtain a desired outcome. It is assumed that the cat pushes the vase to break it, not because it is curious of the effect.

Previous experience and knowledge about one's surroundings allow for making informed choices to steer the system to the desired effect. This principle of initiating a cause to get the desired effect is the core concept of control. Cybernetics is about consciously choosing the causes that have the desired effects. Cybernetics can thus be defined as the study of cause and effect and how the principle may be inverted to obtain the desired outcome.

There are unintended and intended choices. Unintended choices, e.g. a distant butterfly flapping its wings, are choices the steersman of the system has no control over, though they still might influence the system. Even intended choices are not fully informed, as all information around a choice is not available within the defined system boundaries. These factors, materialising through disturbances and noise, will often lead to deviations between the desired effect and the actual effect. In section 2.2.3 those disturbances were denoted w, and the system must reconsider to obtain its desired outcome, like in Figure 2.42. When the system reconsiders this way, it is closed-looped.

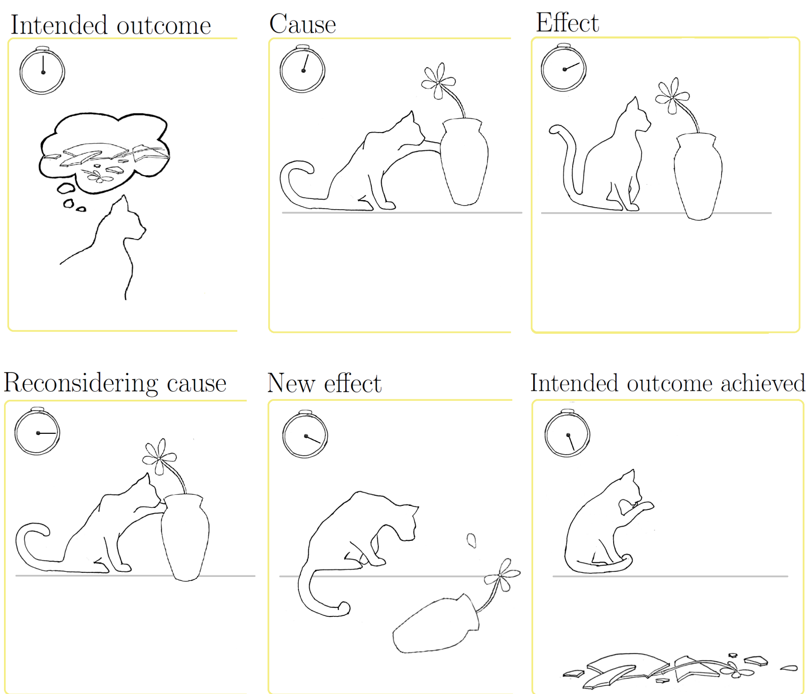

Figure 2.42: Feedback is introduced as the cat reconsiders the cause.

A closed-loop system is characterised by setting a goal, taking action, checking if the goal is reached, adjusting the action and repeating until the effect is satisfactory. The reconsiderations might occur once an hour or a thousand times per second, depending on the chosen time step. It does not matter how frequent they occur, but once a choice is made, it is in the past and is impossible to change.

Cybernetics is an old science. The closed-loop system is dynamic, using the information in and around the system to continuously adapt. This behaviour is true both for animate and inanimate systems automatically controlling themselves, and the principle is the same whether the desired effect is conscious or unconscious. Numerous systems in living, social and technological sciences may be understood this way, as illustrated in Figure 2.43. It is the core of thermostats, cells, bodies and autopilots. It takes part in politics, management, family therapy and pedagogy, in natural sciences, arts and humanities, mirroring the interdisciplinary nature of the subject (Ridderbos 2002). Cybernetics is at work all around the world all the time. However, the science has only been "discovered" in the last century and implemented in machines through engineering cybernetics.

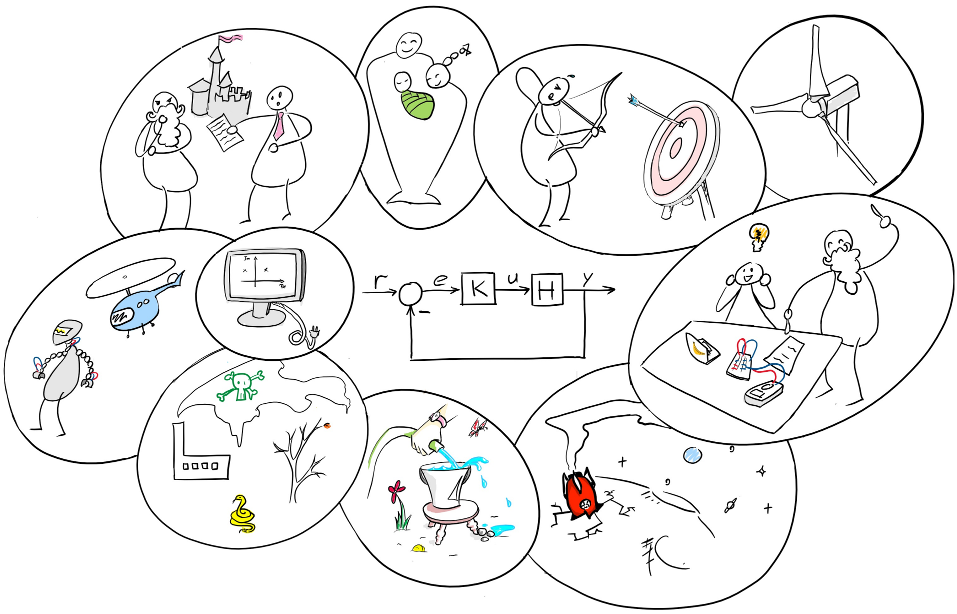

Figure 2.43: Numerous systems in living, social and technological sciences may be understood through cybernetics.

2.3.4 Engineering Cybernetics

Engineering cybernetics aims to synthesise the automatic behaviour in animate systems and implement it in machines. The physical world may be observed and interpreted in the mental world, translated to the mathematical world, and realised in automatic control systems in the physical world. In Figure 2.37 this connection was illustrated in a triangle, though when following the progress of time, it will look more like Figure 2.44.

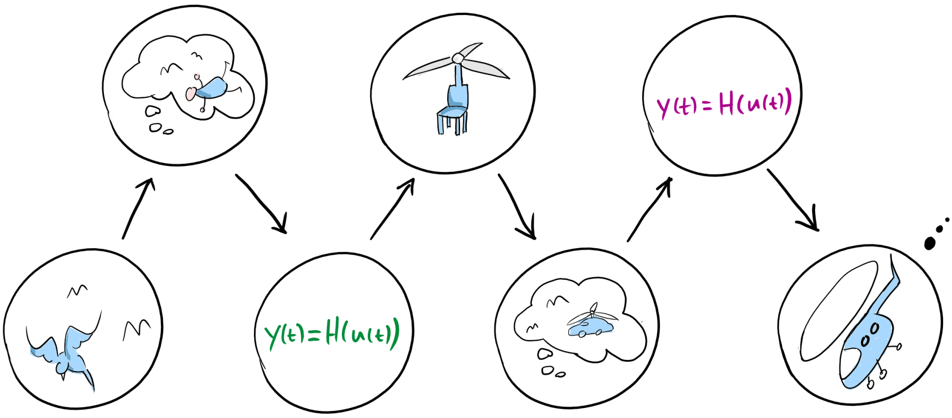

Figure 2.44: The idea development process is also a closed-loop system characterised by setting a goal, taking action, checking if the goal is reached, adjusting the action and repeating until the effect is satisfactory. But time moves forwards as the process develops, and the triangle may be modified to a zigzag.

Just like in animate systems, a program must gather data to make informed choices to get the desired outcome. Communication is needed when collecting data but also when conveying commands to the machine. Communication involves translating physical effects affecting the system and spoken commands in English into a language that computers understand.

As was clear in the mathematical analysis, all the data is never available. Despite there being one past, all the information on the past is not available, and the path is often unknown. The evidence of the choice might still exist in memory (if someone saw the cat push the vase); or physically (the vase is shattered on the floor), making it possible to estimate what probably has happened. Estimation was introduced as a central part of cybernetics in section 2.2.3.

Control is the other important aspect of cybernetics. It enables technology that would otherwise be impossible. This became obvious under the rise of cybernetics during World War II. Wiener (1985) wrote how the speed of aeroplanes had rendered obsolete the classical air defence systems even before the war. The missiles were barely faster than the planes they were supposed to shoot down. It became clear that the missile must be shot not at the target, but in a way that caused the missile and the target to come together in space at some time in the future. A program needed to be built into the air defence systems to predict the future position of the plane and act accordingly.

Ever since the war, engineering cybernetics has provided a means to develop efficiency and efficacy in technological systems. The science may be used to build models and simulations, testing and making predictions; it allows to select and build the ideal hardware and may be used to understand the dynamic interactions within the system (Douglas 2019). The science provides a way to manage global challenges while creating new sustainable and humane jobs. The science also plays an important part with its sheer multidisciplinarity. As Wiener (1985, p. 2-3) stated,

> If the difficulty of a physiological problem is mathematical in essence, ten physiologists ignorant of mathematics will get precisely as far as one physiologist ignorant of mathematics, and no further. If a physiologist who knows no mathematics works together with a mathematician who knows no physiology, the one will be unable to state his problem in terms that the other can manipulate, and the second will be unable to put the answers in any form that the first can understand.

The global challenges are not merely biological or mathematical, or sociological. They are intricate and often hard to label. Engineering cybernetics provides a way to weave all other engineering fields together. Even though the interdisciplinary nature of the subject provides a challenge for the students learning it, cybernetics engineers have a broad knowledge of many subjects. It is of a different paradigm than other sciences, as it is not a "thing" or a defined field, but a behaviour. Physics, statistics and ICT are traditional sciences that can be studied individually, but can also be studied from a cybernetic point of view. Furthermore, cybernetics depends on these sciences to be expressed. The fundamentals of control cut across many traditional boundaries, and with this viewpoint, a broad spectre of engineering problems can be solved.

Chapter 3

Pedagogy

Humans have tried to understand the world for ages, passing knowledge from teacher to student and steadily improving their living standards. The approach to teaching is called pedagogy, and good pedagogy determines how well the knowledge is transferred. However, there is much controversy on what makes pedagogy *good*. As Hess and Fore (2018, p. 551) put it,

> [...] there is neither a consensus throughout the engineering education community regarding which strategies are most effective towards which ends, nor which ends are most important.

The task of summarising relevant literature is not an easy one. There is an ever-growing amount of available literature that differs greatly in methodology and quality. Much is guesswork based on weak evidence (Henderson et al. 2011). There are often unclear definitions of what works and what are significant improvements (Donovan et al. 2000, Prince 2004). Much literature emphasises the problems of traditional education without displaying any concrete solutions. Clear and unambiguous instructions are rare, as are instructions on a practice that works on more than one field (Prince 2004).

Despite the varying quality of the literature, there is a general consensus that active learning is superior to traditional teaching methods. By using a diverse collection of sources, from articles recognised worldwide to small Norwegian conferences, this chapter aims to make a factual statement of what is "good" pedagogy for engineering education. The principles of learning are analysed in the first part of the chapter, whereas the second part is centred around the learning process and strategies that enhance students' learning.

3.1 Learning

Learning is, in this thesis, defined as the process of acquiring knowledge, skills and attitudes (Rugarcia et al. 2000, Crawley et al. 2011, Leithwood et al. 2019) within a given topic. Knowledge (knowing that) is having facts and information, solving theoretical problems in a theoretical understanding of the topic. Skills (knowing how) is the ability to do something in practice in an applied understanding of the topic. Attitude is the values, motivation and inspiration that drives people to learn or the negative associations that stalls learning. These three components, illustrated in Figure 3.1, are equally important in learning through all stages and ages in life.

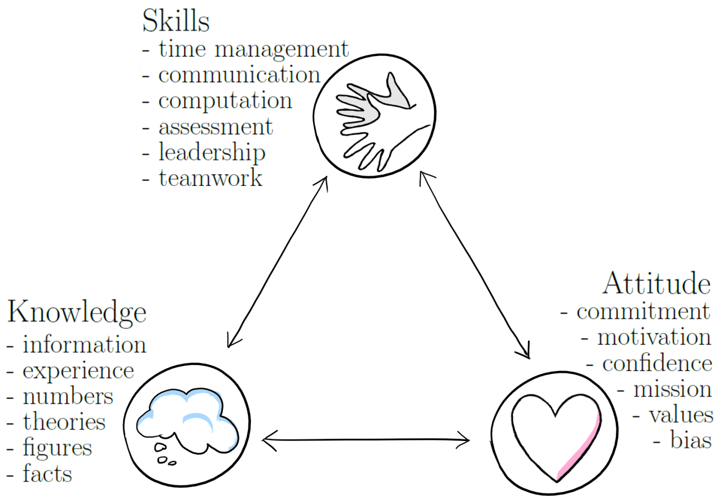

Figure 3.1: The learning triangle.

3.1.1 Attitude

The attitude people have to learn greatly influences their success in learning (Rugarcia et al. 2000, Credé and Kuncel 2008, Hascher 2010, Marchand and Gutierrez 2012, Lewis 2013). Attitude is, according to Oxford Languages (2021), "a settled way of thinking or feeling about something." Attitudes are thus closely connected to emotions (Petty and Briñol 2014), which in turn are interconnected with neurochemistry. Without going into detail, some chemicals influence or control brain functions and the control of emotion. Dopamine is most commonly tied to pleasure in everyday language, though it allegedly boosts motivational salience (Nestler 2001, Baliki et al. 2013, Wenzel et al. 2014). Other neurotransmitters are involved in mobilising the brain and body for action, in cognitive functions such as learning and memory in the brain and regulating mood and appetite.

Due to these chemicals' power over human behaviour, the student's emotions should be considered in learning settings. Motivation, inspiration and goals might spark emotions and create a feeling of well being, having a positive impact on results (Walkington et al. 2020, Credé and Kuncel 2008). Academic specific anxiety and the discomfort that follows has negative impacts (Credé and Kuncel 2008, Lewis 2013). Learning is a process that includes success and failure, and the student's emotions and attitudes must be considered.

3.1.2 Knowledge

Knowledge refers to the theoretical understanding of a concept, information, numbers and descriptions, and how the facts and figures relate to each other (Rugarcia et al. 2000) as a whole. Building knowledge is like puzzling together a picture. There is no value in memorising all the separate parts, but a mental picture appears when piecing together the information.

Traditional assessment methods like exams and written assignments aim to measure students' knowledge (Rugarcia et al. 2000, Magana et al. 2017). However, cramming and memorising facts is often sufficient to pass the test, encouraging learning inefficiencies. Consequently, learning gets harder as the students progress their education, as their knowledge foundation is weak (Oakley 2014). Lacking knowledge within key concepts makes further learning impossible, and the student must continue to cram the necessary information to pass the test until that is no longer possible.

3.1.3 Skills

It is not sufficient to have theoretical knowledge of a subject in an engineering context. Higher education must face the needs of the customer (Violante and Vezzetti 2017), and the companies that higher graduates are interested in employees that can perform work. In Figure 3.2, all the theory is written on the blackboard. A student who understands the history and structure of a bike does not necessarily know how to ride a bike. Skills are needed in addition to knowledge, i.e. they must have the ability to do something in practice.

Bike riding may seem trivial compared to solving engineering problems. But the first time a child tries to balance a bike might seem just as overwhelming as the first time they are introduced to a second-order differential equation. In both cases, it is not sufficient to know the theory.

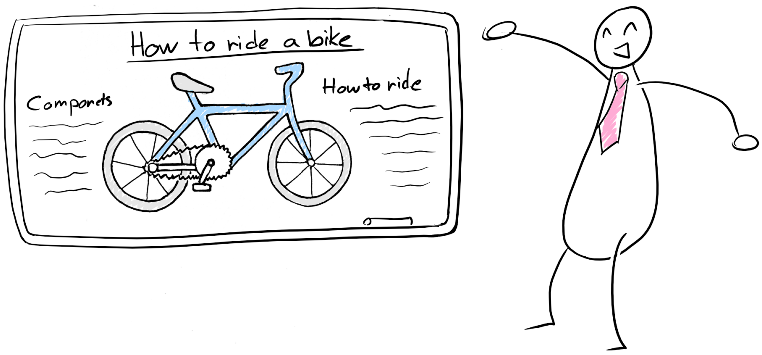

Figure 3.2: "Now you know how to ride a bike!". Bike riding, in theory, includes learning the components of the bike, maybe some history about the bike and a description on how to use it.

ABET (2021, p. 5-6), an ISO 9001 certified organisation that accredits university and STEM college programs, defines the necessary learning outcomes for engineering programmes as (reproduced with consent):

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

These learning outcomes are formulated as abilities, i.e. skills, but also depend on knowledge and values. They may be summarised in simpler language to learning skills, problem-solving skills, communication skills, critical thinking skills, teamwork skills, assessment skills and change-management skills. Several other sources report similar necessary skills, including Rugarcia et al. (2000), Violante and Vezzetti (2017), Kunnskapsdepartementet (2017), Ramirez-Mendoza et al. (2018).

3.2 Active Learning and Kolb's Learning Cycle

Traditional programmes at university level generally aim to teach students their trade through a range of parallel courses (Guerra et al. 2017). The courses are organised based around the course syllabus, which is given through a series of lectures (Lundheim et al. 2021), often looking like Figure 3.3. The lectures are supplemented with student activities of varying quality (Lundheim et al. 2021) and students learn to pass the exam and forgetting the content after (Rugarcia et al. 2000). There is little interaction between participants and teacher, students are largely passive, and the learning outcome is less than desired (Mulryan-Kyne 2010). However, it is easy to implement in large courses and therefore favoured. But as Volpe (1984, p. 433) stated,

> What is urgently needed is an educational program in which students become interested in actively knowing, rather than passively believing.

Even after completing years of school, many university students employ inefficient learning strategies (Kiewra 2002, Bunting 2020), and are stuck in a passive learning mentality. Messineo (2018) lists five common learning errors as inattention, decontextualisation, conflicts with previous knowledge, absent or ineffective practice, and isolated learning. Subject curricula often present too many disconnected facts in too short time (Donovan et al. 2000). If the content is to be understood, teachers must engage students' existing knowledge. Introducing novel concepts by first creating a framework and experiences so the new information can find its place in an order and hierarchy (Messineo 2018).

The essence of education is that the students make sense of the information they receive. Several sources (see e.g. Donovan et al. (2000), Ramsden et al. (2007), Ramirez-Mendoza et al. (2018)) demand teaching methods that promote more meaningful and long-lasting learning.

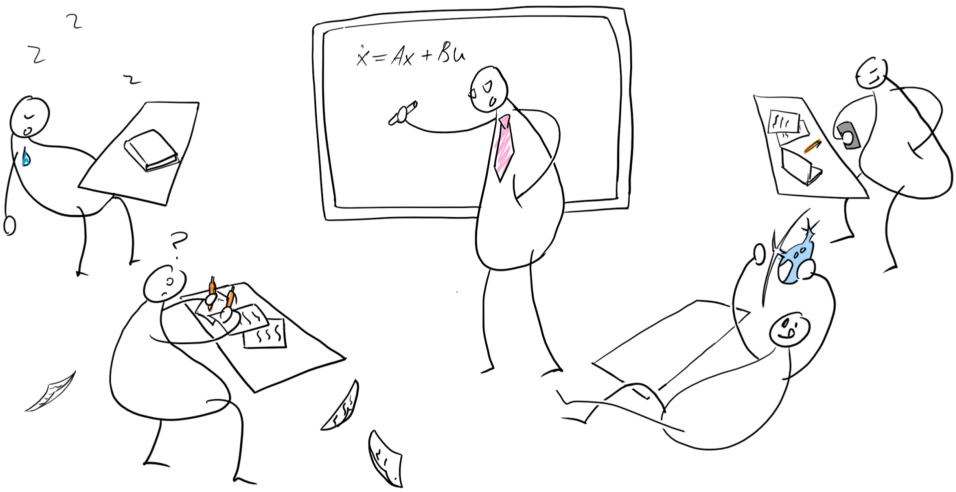

Figure 3.3: Passive learning is typically centred around a textbook or a curriculum. Students often have weak self-motivation, avoids responsibility for learning, comes to class unprepared and receive the information without question. They hear the speaker, copies to notes, reads, rereads and does what is expected to get a good grade. (Prince 2004, Michael 2006, Mulryan-Kyne 2010)

Active learning is centred around the student and their learning instead of the syllabus and textbook (Ramsden et al. 2007). Active learning includes (Prince 2004, Michael 2006, Mulryan-Kyne 2010) instructional methods that engage students in the learning process, developing autonomy and independence to understand the content on their terms by reasoning and critical thinking. It may be realised through actively participating in research, project work and other tasks where they are kept mentally and sometimes physically active and may look like Figure 3.4. The students will use their experience to answer the exam.

Active and passive learning are not mutually exclusive, and lecturing may have aspects of both. However, there is a general consensus that active learning is superior to traditional teaching methods (Driver et al. 1994, Donovan et al. 2000, Ramsden et al. 2007, Ramirez-Mendoza et al. 2018)). Michael (2006) concluded that there is evidence supporting active learning, not through a single, definitive experiment, but by the diversity of sources of evidence. Prince (2004) found that the support for active learning is broad but uneven, and while it will not always show on test scores, it might influence study habits and attitudes, leading to more long-term remembering and understanding.

Figure 3.4: Active learning traits include student-centred learning where the teacher is facilitator and co-learner. Students have strong self-motivation, take responsibility for learning, prepare for class, are alert, open-minded, and ready to explore, reflect, and criticise information. They read, reflect, connect concepts into a conceptual framework and to the world, and learn to apply knowledge to solve problems. (Prince 2004, Michael 2006, Mulryan-Kyne 2010)

Freeman et al. (2014) found that classes with traditional lecturing were 1.5 times more likely to fail than active learning sessions and that the latter had an average improvement of 6 % in the examination scores. Many other studies report benefits with active and student-centred learning, some of them being Volpe (1984), Bonwell (1991), Rugarcia et al. (2000), Besterfield-Sacre et al. (2014), Fiorella and Mayer (2014), Magana et al. (2017), Kozimor-King and Chin (2018), Misseyanni et al. (2018), Shi et al. (2019b). The conclusion is thus that knowledge in engineering higher education cannot be transmitted; it must be actively learned.

One of the most widely influential and cited models that promote active learning is Kolb's learning strategy. Kolb described the learning process as a four-stage cycle: (1) concrete experience, (2) reflective observation, (3) abstract conceptualisation, and (4) active experimentation (Kolb 1984), as illustrated in Figure 3.5.

People learn differently, and different students prefer different combinations of the steps in Kolb's learning cycle Lu et al. (2007). As is always the case when social sciences are involved; it is impossible to make one strategy that fits all.

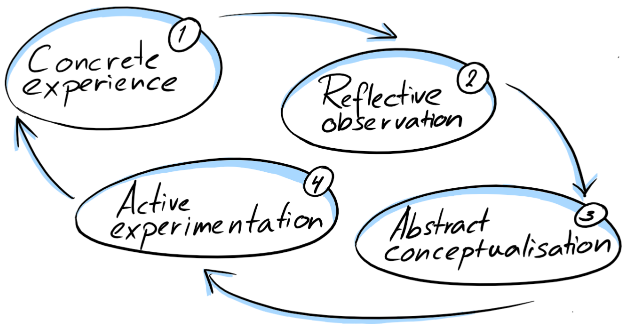

Figure 3.5: Kolb's learning cycle.

Lectures do not cover all Kolb's learning cycle elements and must thus be supplemented by alternative strategies. Alternatives to lectures have always existed, especially in disciplines such as music, arts and crafts (Lundheim et al. 2021). Some alternatives are

- Lectures
- Cooperative learning
- Collaborative learning
- Game-based learning
- Peer instruction
- Problem-based learning
- Project-based learning
- Flipped classroom

Note that several of the models are partly overlapping.

3.2.1 Lectures

Lectures based approaches are traditionally the main way of presenting content in universities. Often the lecture is monologues that directly follow existing documents, giving little incentive for students to attend (Mazur 2017). Therefore there is growing opposition to lectures. But "The problem is lousy lectures, too many lectures, and lectures for the wrong purpose." –(Kozimor-King and Chin 2018). It would be wrong to reject all lectures completely because of a notion that lectures are bad (Mulryan-Kyne 2010).

> Lundheim et al. (2021) has developed a teaching model that combines problem-based learning with lectures. The model is implemented in the subject TTT4203 – Introduction to Analog and Digital Electronics at NTNU. The subject is developed around activities that promote the students learning. The student feedback is positive (Lundheim 2021).

3.2.2 Cooperative and Collaborative Learning

Collaborative learning (Figure 3.6) implicates joint intellectual efforts by students and sometimes teachers toward a joint goal. In contrast, each student is assessed individually in cooperative learning and is held responsible for contributing to the success of the group (Guerra et al. 2017, Misseyanni et al. 2018). There is value in group discussions to create a conceptual understanding, groupmates holding each other accountable to learn, providing feedback and encouraging further learning (Johnson et al. 2014). An appropriate physical learning environment, like the one illustrated in the figure, facilitates CL (Lundheim et al. 2021).

Figure 3.6: CL in a fitting physical learning environment.

Cooperative and collaborative learning (CL) is different from competitive and individualistic learning. Whilst they have benefits (as manifested under the section addressing gamification), cooperation is a fundamental part of human behaviour. Engineering is a cooperative enterprise, where people with different abilities and experience work together (Rugarcia et al. 2000) and cooperative and collaborative skills are thus essential to learn.

The social aspect of CL is equally important as the professional aspect (Gillies 2016). Johnson et al. (2014) writes how CL promotes self-esteem and social competencies, (i.e. psychological health) and positive attitudes toward the university experience. Further, it might benefit the individuals' attitude towards their programme and establish their identity as part of a group. The social-psychological aspect of CL makes it a foundation for other forms of active learning. (Johnson et al. 2014)

The theoretical basis for cooperative learning is rich (Johnson et al. 2014). Meta-analyses and studies reveal positive effects of cooperative learning on achievement and attitudes (see e.g Kyndt et al. (2013), Tran (2014), Capar and Tarim (2015), Foldnes (2016), Munir et al. (2018)). The consistency of the results despite the diversity of the CL methods arguments for its effectiveness (Johnson et al. 2000).

> Experts in teamwork (EiT) is an obligatory course for all master programmes at NTNU. Its purpose is to develop interdisciplinary collaboration skills by focusing on effective teamwork while solving tasks (NTNU 2021). The course won the Norwegian Education Quality Award in 2002 (NOKUT 2017) and again in 2021 (Diku 2021a).

3.2.3 Game-Based Learning

Learning is often associated with work and boredom, while games are associated with free time and fun. Game-based learning and gamification use games to improve the learning experience (Misseyanni et al. 2018) and, more specifically, their motivation. A motivated student can learn almost anything (Prensky 2003), as an improved attitude decides the time and the approach the student is going to use on the content. An example of game-based learning is given in Figure 3.7, where the students are motivated to try again if they fail. The competitive aspects may also be of value.

The game can be an online quiz where the students compete against each other (like Kahoot), board games or card games with educational undertones, play and role-play or other stimulating activities (Subhash and Cudney 2018). Game-based learning differs from CL as it is competitive and individualistic (Johnson et al. 2014). Competitive instincts and rewards may motivate students, complementing CL.

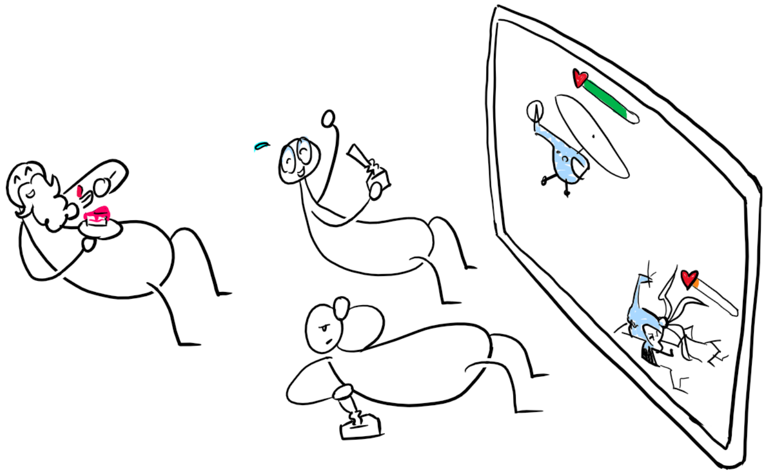

Figure 3.7: Game based learning appeals to the learner's attitude.

There is evidence that games improve student outcomes and student enjoyment (see e.g. Blunt (2007), Ebner and Holzinger (2007), Sailer and Homner (2019), Tsai and Tsai (2020). There is not much literature on gamification in engineering higher education, but generally, games seem to engage and motivate students and improve their performance (Subhash and Cudney 2018).

YouTuber and former NASA engineer Mark Rober asked his (then) three million followers to complete a simple computer programming puzzle, augmenting that anyone can learn to code. Fifty thousand people participated, not knowing that the game was given in two versions. In one version, the player was penalised for failing by losing points, while the other version simply asked the player to try again.

The second group had a success rate of 52 % against 68 % in the first group. The data showed that the people who didn't see failure in a negative light had nearly 2.5 more tries and learned more. The same effect is well known in the gaming industry, where players learn from their mistakes and try again. Rober, therefore, called the motivation from games the Super Mario Effect, after the popular game. (Rober 2018)

3.2.4 Peer Instruction

Peer instruction (PI) is based on the idea that a student is more likely to understand a concept explained by a fellow student than if it is explained by a professor (Mazur 2017). The students are given tasks that require them to understand the core concepts being presented, thus uncovering difficulties with the material (Crouch and Mazur 2001). The peers then explain it to each other. Because they know the learning difficulties, they describe the content to their peers with this in mind, as illustrated in Figure 3.8.

Figure 3.8: A peer will explain the content differently than a professor. Sometimes it helps just to hear the explanation from a different angle.

Several studies (Fagen et al. 2002, Zhang et al. 2017, PhysPort 2021) show how classes taught using PI improved student attitudes and beliefs compared to the control group. PI is a form of CL, and the strategies share many benefits.

ONE2ACT is an online-based response system with game elements. It includes a Student Response System and a Peer Learning Assessment System, allowing for anonymous interaction between student and teacher. The latter allows the students to learn from each other through discussions and group work in peer instruction. (ONE2ACT 2021)

3.2.5 Problem-Based and Project-Based Learning

An engineer's trade is to solve problems. Engineers meet open-ended, disorganised and complex problems that demand multidisciplinary perspectives (Jonassen et al. 2006). It makes sense for engineering students to learn how to solve workplace problems (Jonassen et al. 2006, Hung et al. 2008). But the problems engineering students solve in class are often very different and does not necessarily prepare them for working life as engineers (Jonassen et al. 2006).

Problem-based learning (Figure 3.9) is designed to prepare students for solving problems in a working setting by embedding students' knowledge in real-life settings instead of studying content and applying it in context-free problems (Hung et al. 2008). It also allows for the content to be adapted to the needs and background of the individual student (Lundheim et al. 2021). For this reason, Problem-based and project-based learning (PBL) has been adopted into engineering education (Chen et al. 2020).

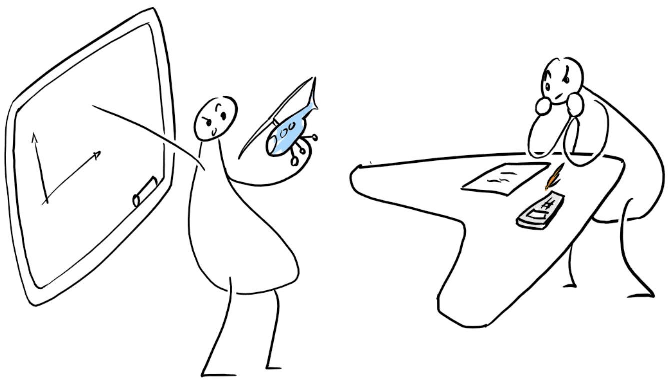

Figure 3.9: PBL is designed to prepare students for solving problems in a working setting.

Problem-based learning reverses traditional teaching methods, giving students an appropriate problem and tasking them to develop a procedure to solve it (Misseyanni et al. 2018) (Wood 2003). Project-based learning is essentially the same but centred around a project. The problem may be a real challenge within society, to develop a definition on a concept, to build an open-ended product or something completely different. The problem may be solved in teams or individually. PBL implementation varies widely, but the fundamental principle remains (Edström and Kolmos 2014, Chen et al. 2020).

Of the same concept as PBL is conceive–design–implement–operate (CDIO) that is specifically developed for engineers. CDIO is a method used on real systems and processes by real engineers, and students may thus benefit from learning the process. Whereas PBL emerged from rethinking the process, CDIO was developed from rethinking the learning outcomes. Therefore, they partially overlap as strategies for educational reform. (Berggren et al. 2003, Edström and Kolmos 2014, CDIO 2021)

Studies (binti Mustaffa et al. 2014, Alves et al. 2015) show that PBL has a positive impact on learning outcomes of science students, and according to Alves et al. (2015) PBL may help students grasp how the individual courses fit together in their programme. PBL is often incorporated through assignments and laboratory exercises, but there is potential in breaking the traditional barriers between classes to create longitudinal project work across the programme (Brajkovic 2020).

Students' first meeting with research is often through a bachelor's or master's thesis in their final year. There might be value in connecting students with the community through research earlier. Students, faculty and community might research together to solve a problem or make a change in society (Kozimor-King and Chin 2018). Closer cooperation between universities and industry may benefit both parties, focusing on relevant knowledge for the industry and emphasising skills and competencies.

As part of the programme Electronic System Design and Innovation at NTNU, the students design and realise a project defined together with an external partner (IES, 2021). The project given in 2014 was to create a boat guard. Two students developed their solution further, and the project is now funded and installed on several boats (Askeland, 2021). The project To Build Brains given in 2015 has also been realised and commercialised (Kvello and Lundheim, 2021).

3.2.6 Flipped Classroom

The standard approach to teaching aims to transfer information is in the classroom, leaving the sense-making out of the classroom. Flipped classroom (FC) reverses the typical dynamics of lecture and homework, recognising that the harder part is the sense-making (Mazur 2017). Students learn the theory at home, whilst the class is used for solving problems, projects and discussion and clarifications (Misseyanni et al. 2018).

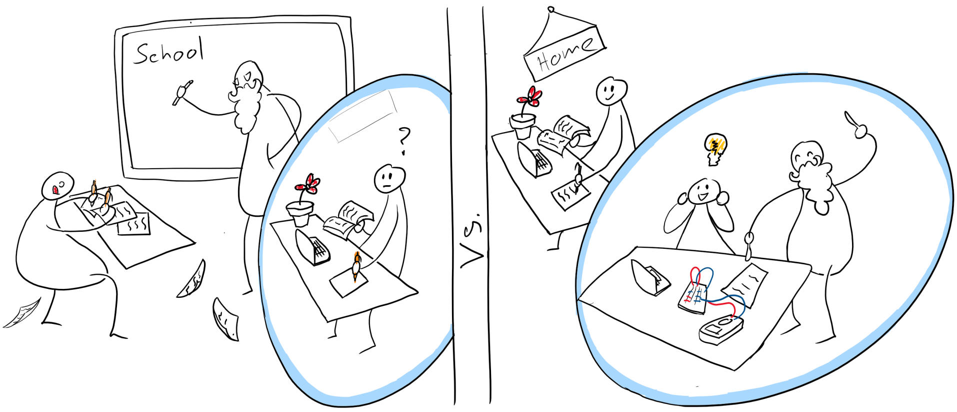

Figure 3.10: Flipped classroom fundamentals.

Kozimor-King and Chin (2018) experienced that the flipped classroom engages students far better than other models. They reported a decrease in Ds, Fs and student withdrawal with the use of flipped classroom and an increase in As and Bs. Chen et al. (2018) reported greater academic achievement with FC than with the traditional lecture-based approach, though the examined studies suffer from great methodological diversities. Cheng et al. (2018) and Shi et al. (2019a) reported a positive effect on students' cognitive learning outcomes on FC compared to the traditional approaches. (Munir et al. 2018) showed results that indicated flipped classroom as a help to develop and improve students' learning and critical analysis skills, especially (Foldnes 2016) if properly implemented with cooperative learning.

> The subject TTT4203 – Introduction to Analog and Digital Electronics was introduced in the fall of 2020 at the Department of Electronic Systems at NTNU. It is based on the flipped-classroom model, and the chore principle is to learn by experience, reflection and training. Student assistants have an increased role in the learning process, and skill training is made more available by handing out electronic kits to the students. (Mikkelsen 2020a)

3.3 Teaching

A teacher is a person that facilitates the learning of a student. In engineering higher education, the teachers are also researchers. According to Michael (2006, p. 165),

> As scientists, we would never think of writing a grant proposal without a thorough knowledge of the relevant literature, nor would we go into the laboratory to do an experiment without knowing about the most current methodologies being employed in the field [...]. Yet, all too often, when we go into the classroom to teach, we assume that nothing more than our expert knowledge of the discipline and our accumulated experiences as students and teachers are required to be a competent teacher.

Johnson et al. (2014) states a similar reason for the slow development in teaching methods. Scientists never make statements and claims before checking for facts. The same approach should be obvious for teachers (Mazur 2017).

Progress is not possible if the teaching is based on uncontested folklore and gut feelings rather than conclusions from rigorous research (Johnson et al. 2014, Wenner and Campbell 2016). Educational decision making must be based on high-quality, rigorous research (Michael 2006, Henderson et al. 2011, Johnson et al. 2014) and must be consistent with modern theories of learning (Felder et al. 2000a). Then, education can progress and keep up with the technological and social development of this world.

For many years education has been criticised for dampening creativity rather than fostering it (Gibson 2010). Lundheim et al. (2021) suggests that despite attempting to implement creative student activities, the program will still be teacher and syllabus centred if the planning of a course starts with setting up a lecture plan or choosing a syllabus book. Thus, the student will be more drawn to what the syllabus defines than what they achieve in terms of learning. A change of attitude towards the learning process is necessary for a paradigm shift.

Felder et al. (2000a, p. 16) formulated teaching techniques that have been repeatedly shown to be effective in engineering education:

1. Formulate and publish clear instructional objectives.

2. Establish relevance of course material and teach inductively.

3. Balance concrete and abstract information in every course.

4. Promote active learning in the classroom.

5. Use cooperative learning.

6. Give challenging but fair tests.

7. Convey a sense of concern about students' learning.

The techniques of Felder et al. is only one approach to teaching. However, it shows clearly that the teacher is more than a conveyor of information. Wherever humans are concerned, interactions become more complicated than giving commands. The humane perspective of seeing every student and facilitating their individual needs may be the hardest part of teaching.

> The Norwegian National Body for Quality in Education (NOKUT) and later the Directorate for Internationalisation and Quality Development (Diku) works to ensure the quality of Norwegian education. One strategy is to appoint the status of Centre of Excellence in Education (SFU) to Norwegian educational environments. The SFU scheme stimulates research-based teaching methods that provide increased quality in higher education, both inside and outside the host institutions and promotes interactions between students, teachers, support services and the education's knowledge base (Diku 2021b).

3.3.1 Leading

Leadership is not defined in the role description of teachers. However, the job is grounded in other leadership theories, like establishing relationships, breaking down barriers and marshalling resources to improve students' educational outcomes (York-Barr and Duke 2004).

When social and human sciences are concerned, leadership may be argued to be one of the most important issues (King et al. 2009, Hogan and Kaiser 2005). Good leadership promotes human interaction and thus enhances the individuals' well being, whereas bad leadership degrades the quality of life for the ones associated with it (Hogan and Kaiser 2005). Also, the active learning process is unpredictable and uncertain, and it is crucial with proper management if it is to succeed (Misseyanni et al. 2018).

Teachers perception of leadership seems to positively influence student outcomes (Martin et al. 2003, Ramsden et al. 2007). Leadership is a key factor to improve learning and teaching in higher education (Hofmeyer et al. 2015). Teacher leadership is essential in providing excellent higher education (Zhang et al. 2021). However, leadership in teaching is highly context-dependent, and one strategy cannot be implemented in another subject just like that (Gibbs et al. 2008).

When it comes to the leadership role of teachers, good leadership will stick to the students after the person leaves (Fullan 2017). The leadership should be value-driven, engaging followers through inspiration, exemplary practice, collaboration, spontaneity and trust (Ramsden et al. 2007). Teachers should lead students through the learning process until they become independent. Eventually, the learners may adopt the efforts of the teacher as a learning skill, making the students the key agents of their own academic success (Sambell et al. 2017) as independent learners.

Teach First Norway is a two-year leadership development programme for newly-educated graduates holding a science degree. The initiative is a partnership between Oslo Education Agency, the University of Oslo and Equinor. The candidates follow a special program that combines leadership training with the teacher role. Teaching STEM subjects at selected schools in Oslo, they receive formal teaching education and leadership training. (Teach First Norway 2018, Equinor 2021)

A good leader must facilitate learning. Whether students are proactive and engaged in the classroom or reactive and passive depends partly on the quality of the classroom climate in which they learn (Reeve 2006). The classroom should feel safe so that students are free to focus on tasks (Misseyanni et al. 2018). Norms that encourage critical thinking and questions (Donovan et al. 2000), that promotes inquiry (Kozimor-King and Chin 2018), creativity, discussion and teamwork and lifelong learning (Kozimor-King and Chin 2018, Misseyanni et al. 2018) ought to be implemented. An environment where students are motivated by the course, program, and instruction (Misseyanni et al. 2018) to gain the knowledge, skills and attitudes that are necessary for working life (Rugarcia et al. 2000), that motivates the students to learn (Misseyanni et al. 2018). The role of the teacher is not only telling them what to do but asking the right questions and guiding the steps of the students, as in Figure 3.11.

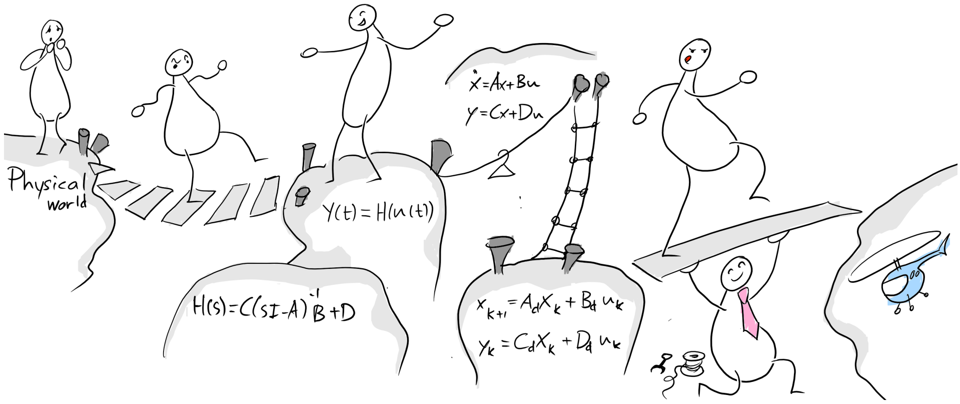

Figure 3.11: A teacher facilitates learning.

By supporting the inner motivational resources rather than frustrating the student (Reeve 2006), taking their perspective, acknowledge and accepting negative effect (Reeve 2016), the teacher may contribute to a high-quality teacher – student relationship (Reeve 2006). Focusing on the purpose of teaching, i.e. learning and a holistic understanding, is just as important as the content (Quinlan 2014).

Tasks should be challenging enough to maintain engagement, but not so difficult as to lead to discouragement (Felder et al. 2000a). Teaching students to plan tasks, notice patterns, generate reasonable arguments and draw analogies to other problems in a structured mental information base (Donovan et al. 2000). Encouraging monitoring and reflection (Woods et al. 2000), so the students learn meta-cognitive behaviour (Donovan et al. 2000). Experts work this way, and the abilities can be taught and learned, and the students may graduate as proficient engineers.

Other important factors for academic performance include time management, study aids, self-testing and test strategies (Credé and Kuncel 2008). Exercise, sleep and proper nutrition are also crucial for the learning experience (Oakley 2014, Messineo 2018). These can be incorporated as part of the curriculum to varying degrees.

3.3.2 Cooperating

At the centre of academia are the teachers that are dedicated to higher learning. The teachers are peers, equals to each other (Lamont 2009) and may benefit from peer learning in the same manner as a student. Peer review and collaborative teaching allow the teachers to learn from each other as in

Figure 3.12. Professors are familiar with peer review when publishing their research and may use this also to quality control their lectures (Klopper and Drew 2015, Harrison et al. 2020). It may prove a safe and supporting way to facilitate professional learning and development Sachs and Parsell (2014). However, opening their classroom to the eyes of their peers may provoke feelings of insecurity (Kozimor-King and Chin 2018).

Figure 3.12: Collaborative teaching may improve education.

Collaborative teaching and partnerships aid the quality of the programme as a whole as well, as several courses become more connected (Kozimor-King and Chin 2018). This approach is radically different from the norm of the professors as a solo instructor in an individual course. Ramsden et al. (2007) writes how an environment where staff freely share ideas and discuss their learning needs has positive impacts on student focus rather than the content focus.

Active learning is a process. The stages of planning, doing, checking, and revising the courses must consciously be incorporated in curriculum development (Misseyanni et al. 2018), and the humane aspect must always be kept in mind.

3.3.3 Overcoming the Challenges

Active learning has some adamant benefits, yet much work is required to achieve it, with many pitfalls on the way (Munir et al. 2018). It is more time consuming than traditional lecturing, but this should be expected as it takes more time to learn than gaining superficial knowledge. Additionally, the teacher has less control. It is more prone to digressions, and students may become distracted.

Active learning appears most effective on small class sizes (n $\pm$ 50) (Bonwell 1991, Freeman et al. 2014) with larger classes more prone to be teacher-focused (Ramsden et al. 2007). As engineers are in increasing demand, classes are getting larger, and campuses are more crowded, which makes it tougher to find available workspaces for the students (Bonwell 1991, Guerra et al. 2017) and equipment in general. Each obstacle and risk can be successfully overcome through thoughtful planning (Bonwell 1991).

Time and money are the two fundamental resources in the current society. Professors, in general, do not have time to research and incorporate a new curriculum. In addition to a possible time-consuming preparation, active learning will often be more time consuming than covering all core material through lectures, which makes it challenging to cover the assigned course content (Bonwell 1991).

Active learning in the classroom will require more preparation for lectures as well as increased use of information and communication technologies, so more money (Misseyanni et al. 2018). Campus must be developed with workspaces that can hold the students. Laboratories, classrooms, libraries and recreational areas are some areas that are needed to lift students attitudes. In some cases, it might not be space for the university to expand, adding to the problem.

In engineering higher education, the teachers are generally also scientists/ researchers, creating a fine balance between research and lecturing. Research provides funding and status and eventually a higher salary. Good teaching has not the same benefits. According to Felder et al. (2000b, p. 2), putting too much effort in the teaching before tenure might be the “kiss of death”. This attitude is not easily changed.

Additionally, many educators lack the pedagogical skill needed to teach efficiently. Workshops and seminars, mentorships, networking, peer review and cooperative learning can be of some help (Felder et al. 2000b). However, many professors will likely resist these measures. Halfhearted implementations is a threat, either because of lacking time or resisting professors. Loss of control or fear of doing so is also realistic. All in all, the incentives for faculty to change are limited (Bonwell 1991). Educational tradition has a powerful influence, and together with the discomfort and anxiety that comes with change, their situation is not ideal (Bonwell 1991).

Excellent teaching should, to a larger degree, be recognised and rewarded. There are already meriting systems in place at several Norwegian universities (Øystein Fimland 2018). The scheme has major shortcomings (Raaheim et al. 2020), however, and has been featured in several news articles in the past years. Unclear criteria, poor information and demotivating feedback for rejected applicants (Mikkelsen 2020b), unfair and biased rejections (Hanger 2020) and different practices in different institutions (Arnesen 2021) are some of the reactions.

NTNU, in collaboration with UiT The Arctic University of Norway, aims to improve the quality of higher education by equating requirements for teaching competence with the requirements for research competence. The project makes it possible to apply for Merited educator (Grepperud et al. 2016).

When it comes to the implementation of active learning, perhaps the most significant threat is that students will not participate (Bonwell 1991), or be outright hostile to change, if they perceive the change as more work (Felder et al. 2000b). Students might criticise the faculty for teaching in unorthodox ways and face backlash from them and their parents.

A solid basis in research is crucial in this context, so the resulting strategies are likely to work. An incentive to get the students aboard might be to explain what is done and why and also implementing challenges gradually. (Bonwell 1991)

3.4 Pedagogical Success Stories

NTNU is a large university with many scientific programmes. Many have overcome the challenges of active learning and are now providing excellent education to their students. Some efforts for quality have already been introduced as examples in grey text boxes earlier in this chapter, but some especially relevant solutions for engineering education deserve some more space.

3.4.1 Credits for Student Team Participation

NTNU has many student projects where students build everything from drones, satellites and rockets to cars, boats and submarines (ITK, 2021). The organisations are largely funded from sponsoring by Norwegian businesses. One of the larger groups is Revolve (Figure 3.13), where a team of 80 students work voluntarily parallel to full-time studies to build a race car. Each year, a new team builds a car from scratch that competes in Formula Student, one of the world's largest engineering competitions for students. The project is a way for students to obtain traits from mechanical engineering and engineering cybernetics to project management. (Revolve, 2021)

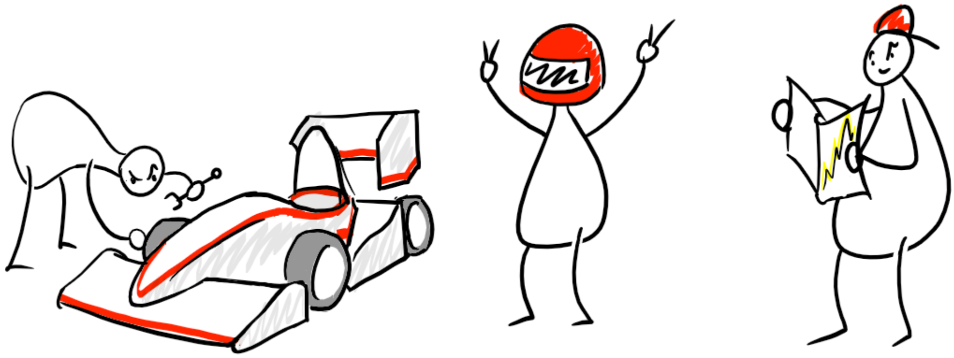

Figure 3.13: Attending the student organisation Revolve may earn students credits for their degree.

The workload of attending such a student team is considerable, especially for full-time students. Because different aspects of the project are highly relevant to all MSc programmes at NTNU, it is possible to get credits for the work. The subject Innovation, Design and Production 1 & 2 (IDP1 and IDP2) has the mission "From theory to practice". By completing some additional assignments throughout each semester, the students get credits equivalent to any other subjects. (IPM, 2021)

3.4.2 Wind Energy Project

The 40 students enrolled on the programme Bachelor of Engineering, Renewable Energy had the compulsorily subject TFNE2004 – Wind Energy, which was assessed purely based on an oral exam and a project report (EPT, 2021). If nothing else is stated, the information is acquired from personal communication of course coordinator Tania Bracchi (2021).

Students gathered in groups to make their very own wind turbine model. They chose their individual specifications and design of both the turbine (Figure 3.14 shows some hypothetical examples) and of the generator's stator. Simultaneously, they attend lectures relevant to the stage of the working process.

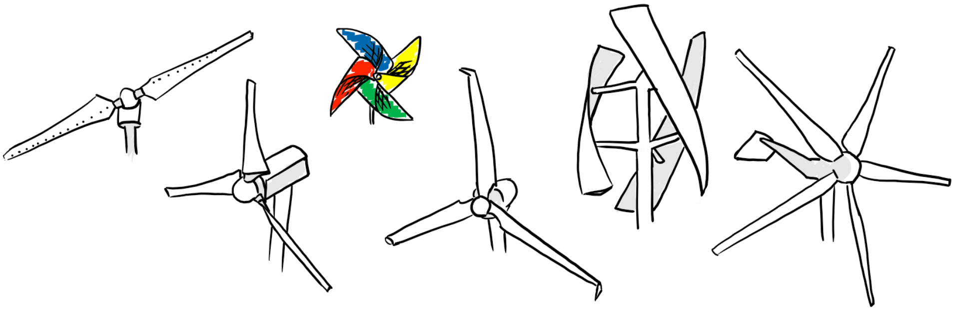

Figure 3.14: The students are allowed to choose their design on the wind turbine model.

Every group made different wind turbines and tested them in the tunnel. Some of the turbines that seemed most promising when simulated, broke in the tunnel under real conditions. Some did not rotate, some performed well, others less so. Some created optimally performing rotor blades and optimally performing generator, but together they did not work well. The turbines with five blades were not necessarily more efficient than those with three blades, and they were more expensive to produce. The practical experiences demonstrated the limitations of model production and the importance of making the system work well, not just the single elements.

The subject has since merged to a larger subject, TEP4175 – Design of a Wind Turbine. Due to the capacity in the model production, the rotor design is now fixed to two blades. Despite there being fewer variables, the turbines still perform quite differently in the wind tunnel. Whilst this kind of project work is time-consuming, the learning outcome is high, and the subject provides meaningful and long-lasting learning.

3.4.3 Electronic System Design and Innovation

A note from two student representatives to the Department for electronics and telecommunications (IES) (Blesvik and Sørgjerd 2009) reported on some possible causes for student dropouts. The possible causes were reported to be (Blesvik and Sørgjerd 2009) (1) the first year's courses were both theoretically heavy and lacking in context; (2) little practical application of theory; (3) a lacking sense of belonging; (4) little inclusive and pedagogical teaching; and (5) poor information flow between students and department. This feedback was one of the incentives for Lundheim (2021) to create the MSc programme Electronic system design and innovation in 2014.

Electronic system design and innovation (Elsys) is organised differently than similar MSc programmes at NTNU in the sense that central courses during the first years are not based on curriculum and textbooks but on activities that the students learn from. The first years of the scientific MSc programmes at the university are characterised by theoretically heavy subjects that create the foundation for programme specific subjects later on. Several hundreds of students attend the same lectures, solving the same assignments and the same final exams. These subjects are necessary also for Elsys students, but additionally, the programme introduces continuous programme specific subjects each semester (IES). These subjects have no textbooks. Instead, the students buy a case with basic electronics – a kind of lab-in-pocket – that is used in all four subjects in a flipped classroom setting, illustrated in Figure 3.15. This collaboration is called the engineering ladder. (Lundheim 2021)

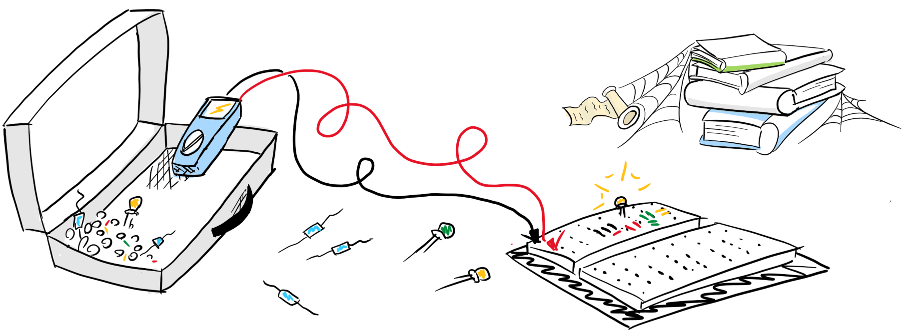

Figure 3.15: The textbooks of four subjects are switched with a lab-in-pocket – a case with electronic essentials.

With a basis in the experiences from these subjects, Lundheim et al. (2021) has developed a teaching model. It is named activity-based subject organising and applies the best from both PBL and lecture-based learning. The model is developed with room for adaptation based on study programs.

The model is inspired by Kolb's learning theories (see section 3.2) to be centred around experience, reflection and training. Students make their own experiences before they are presented with relevant theory. Subsequent lectures and literature then develop these experiences and facilitates new ones. The students then reflect on the consequences of the theory and their experiences. Activities that promote conceptual understanding and pattern recognition by repetition are added for fluidity. Thus, the auditorium is not primarily an arena for the transfer of theoretical knowledge but as a tool for a social community and context around the subject. Multipurpose areas for project-based work are thus of great importance. (Lundheim et al. 2021)

Elsys has been named the best master's program in electrical engineering and mechanical engineering by students in 2018 and 2019. (IES, 2021). According to Studiebarometeret, students from Elsys are substantially more satisfied with their programme than similar MSc programmes at NTNU. The students have rated the programme above average in all of the main categories since the survey started in 2016. Data for 2019 and 2020 is reproduces in Table 3.1.

Table 3.1: Student feedback in 2019 (red) and 2020 (green) for the programmes Elsys, Cybernetics, and the average of similar MSc's (Studiebarometeret, 2021)

	Lectures		Feedback		Expectation		Learning enviornment	
Elsys	4.0	4.0	3.8	3.8	3.5	3.7	4.2	4.2
Cybernetics	3.4	3.6	3.1	3.2	3.2	3.3	3.8	3.7
Average	3.4	3.5	3.2	3.2	3.3	3.3	3.9	4.0

	Organising		Working life connections		Inspiration		Overall assessment	
Elsys	4.1	4.3	4.0	3.8	4.4	4.4	4.6	4.6
Cybernetics	3.9	3.8	3.4	3.1	4.2	4.2	4.4	4.3
Average	3.7	3.7	3.6	3.2	4.1	4.0	4.3	4.3

In the fall of 2020, IES reformed one of the large introductory courses on NTNU based on this model. TTT4203 – Introduction to Analog and Digital Electronics (IES, 2021) was first piloted with 120 students. The course coordinator provided no textbook or syllabus for the course, but it was clear that anyone who understood the activities would do well on the exam. Instead of traditional labs and assignments, the students used their case with basic electronics. Instead of submitting arithmetic exercises, they submitted reflection notes every week, and every second week they met with a student assistant to discuss the student's progress.

IES took these measures to change the focus from the syllabus to activities and understanding. The students experienced a great degree of learning and well being in the course, and the collaboration with student assistants was a success. Even though actual learning outcomes are difficult to measure, the exams were attempted to emphasise conceptual understanding. It seemed that a large proportion of the candidates had achieved a high degree of these learning objectives. The course will be extended to both spring and autumn with 300 – 400 students each semester. (Lundheim et al. 2021).

The MSc programme Electronics Systems Design and Innovation scores far better than similar programmes at NTNU. The results from TTT4203 speaks powerfully in favour of student-centred and active learning as a preferable alternative to traditional teaching methods.

Chapter 4

Case

The fundamentals of control cut across several traditional boundaries, and a cybernetic point of view can help solve a broad spectre of engineering problems. But the educational system is slow to change, not adapting to society's needs.

Strengths, weaknesses, opportunities and threats (SWOT) of the current engineering cybernetic education at NTNU will be analysed in this chapter. The SWOT analysis and the previous chapters make the basis for the case. The case models education as a cybernetic system.

4.1 Current State of Engineering Cybernetics Education

The Department of Engineering Cybernetics (ITK) is seated in Trondheim as part of the Norwegian University of Science and Technology. It was founded in 1954 as the world's first of its kind (Paulsen 2019). It is still one of few such departments worldwide, as comparable departments usually are limited to control theory (Johansen and Hovd 2009). The department has contributed considerably to the Norwegian offshore industry, especially through the development of dynamic positioning for ships (Paulsen 2019) and extraction of petroleum in general.

Three graduate programs are tied to ITK. autoreffig:studyprogrammesa) illustrates the structure of the five-year master program Cybernetics and Robotics (Cyb), where the graduates get the title MSc (ITK 2021a). The title is also given to graduates from the two-year programmes that build on technical bachelor degrees. Figure 4.1b) illustrates the programme that demands applicants to have a bachelor in automation, which gives similar learning outcomes as the five-year programme (ITK 2021b). Figure 4.1c) illustrates the two-year programme that is open to all technical bachelors (ITK 2021c), which provides the graduates with competence on the borderland between cybernetics and the subject area of their bachelor's education. Due to its different nature, the undergraduate program connected to the department will not be included in this report.

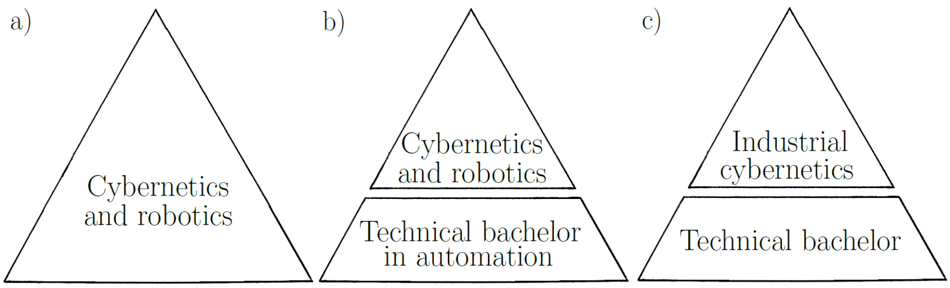

Figure 4.1: Master of Science programmes at the Department of engineering cybernetics at NTNU.

The department has undergone some changes since it was founded, the most radical being the transition from a Sivilingeniør (Diploma Engineer) into a five-year MSc programme (Johansen and Hovd 2009). It required substantial changes in the programme structure and content to fit the rules of MSc, allowing for a thorough review of the course offered (Johansen and Hovd 2009). Since then, it has undergone periodic evaluations and smaller changes (Fossen and Imsland 2019).

4.1.1 Strengths

ITK has a strong position in the Norwegian industry and is also recognised abroad, being among Europe's most well-recognised departments in control engineering, for education and research both (Johansen and Hovd 2009). The department offers Norway's foremost cybernetics studies (ITK 2021c) and is also among the country's most popular IT programs among both genders (Fossen and Imsland 2019).

Countrywide surveys show that Norwegian students are generally satisfied with their studies (Haakstad and Kantardjiev 2015, Lødding et al. 2017, Støren and Nesje 2017). NTNU has some of the country's most satisfied students (Åse Arnesen et al. 2015, Støren et al. 2018, Knapstad et al. 2018), and students at ITK are no exception (Studiebarometeret 2021). Also, the industry is satisfied with the competence of graduated masters in technology (Støren et al. 2019). A survey conducted by Contactor (2021) in February showed that 84 % of the ITK graduates had already signed for a company four months before they submitted their thesis.

The learning outcomes of the five-year program (ITK 2021a) are summarised to (translated from Norwegian):

> The education shall provide knowledge and skills to participate actively in developing current and future business, and it provides a proper basis for demanding duties. The education has a methodological basis that gives the student flexibility and adaptability in a changing labour market.

This quote, as well as the full learning outcomes listed in Appendix A, appear future-oriented and relevant when comparing them to the ABET (2021) necessary learning outcomes for engineering programs. A periodic quality control of NTNU's study programmes (Fossen and Imsland 2019) suggests the same.

4.1.2 Weaknesses

Even with the overall high scores on surveys, the actual scores are somewhat lower. Studiebarometeret (2021) shows a higher rating on social factors and motivation than on academic factors.

The MSc programmes at NTNU are highly theoretical and content-focused. The preferred teaching method is information transmission via lecturing, supplemented with assignments and laboratory exercises, and assessment via one final exam (Fossen and Imsland 2019). By communication with associate professor Morten Pedersen (2021) and colleagues, it also appears that the programmes at ITK lack continuity. There is little to no coordination of the course content. The lacking communication may impact students ability to obtain a holistic understanding of their subject of study.

Whilst the reason for the intricate theory is to ensure excellence, the complex assignments have lead to MCs-students at NTNU adopting a tradition of copying obligatory assignments from each other, either in part or in full (Monsen 2011, Ebrahimi 2011). The tradition is at least two decades long, and even though it is illegal and students risk suspension, it is openly admitted. The complex theory may thus work against its purpose.

Another consequence of the theoretical focus on MSc's at NTNU is that graduates ability to apply their knowledge to new situations is generally inadequate (Støren et al. 2019). Contributing to this is the low academic connections to research and businesses (Haakstad and Kantardjiev 2015, Fossen and Imsland 2019, Støren and Aamodt 2009). There is not much data on ITK specifically, but Studiebarometeret (2021) suggest that connections to the industry are lower than average (see Table 3.1). As companies place great emphasis on relevant working experience (Støren et al. 2019, FINN jobb 2020), this is unfortunate.

The student mass has grown much in the later years. The increasing need for engineers has lead to more students being admitted into the university's programmes, further contorting to the press on the university's areas. Since 1997, the student mass of cybernetics (two-year programmes and five-year programme) has increased from 80 to 180 students per year (Johansen and Hovd 2009, NTNU 2019), and the other programmes have most probably experienced similar growth. Additionally, fusions of universities and campus relocations have moved 2500 additional students and employees into the main campus without building any new areas (Meland 2018). Cramped space and larger subjects with less student-teacher contact (Fossen and Imsland 2019) may be a reason student well being is rated somewhat lower now than in 2016 (Studiebarometeret 2021).

These weaknesses may be the reason that the department's learning goals (appendix A) are not fully reached, even though they, in theory, are adequate. Even though NTNU has a quality control organ, the Reference Group system, it not adequate Sandvåg (2013), Bakke and Haugan (2016), Sindre (2018). It seems to be characterised by half-assessed implementation as a reaction to NOKUT failing the university's quality assurance system in 2013 (Bakke and Haugan 2016, Sindre 2018). The university has not failed the quality assurance system since. Still, as written by Bakke and Haugan (2016, p. 10) (translated from Norwegian): "Even if a system is not bad enough to fail, it does not mean that it is good enough for a university that aims to be internationally outstanding".

4.1.3 Opportunities

Twelve companies that hire cybernetics graduates (2021) were informally interviewed about their views on the cybernetics education at NTNU. The answers, a mix of individual opinions and official statements, show that businesses are generally content with cybernetics graduates but also that there is room for improvement. Several reported that NTNU has a somewhat conservative approach with a more theoretical orientation than other Norwegian universities. Some sources reported that the education, first and foremost, should create a solid foundation for lifelong learning and the ability to acquire skills and knowledge, and that theoretical knowledge was of secondary importance. As working life is oriented around practical problems in various forms, most interviewees reported that the high level of theory with an advantage could be tied to practical experience.

Further, the Twelve companies that hire cybernetics graduates (2021) agreed that projects where the students follow their passion and make their own choices and research is of great value. Several companies reported benefits in attending the student teams mentioned in section 3.4.1. Some companies even sponsor student teams that do similar work as the company and then hire graduates that have attended these teams. None of the interviewees reported collaboration with NTNU other than master's theses, but several responded positively to future cooperation. Some were also willing to sponsor laboratory exercises relevant to their company's work area. Cooperation between business and university is thus an unexploited opportunity.

The programme will also benefit from closer cooperation between teachers, as was stated in section 3.3.2, and between departments. Students from Elsys rate their programme far above average (see Table 3.1), whereas engineering cybernetics students perceive the quality of their programme as average. The two programmes have much in common, the teachers reside in the same building and may learn much from each other.

Closer cooperation with students may also benefit the programme. Whereas professors do not have much time to implement changes, students assistants might be given a larger part in faculty development. Some students have large responsibilities in volunteer work in their free time, and devoted students can develop excellent laboratory exercises and continuity within subjects with some supervision from faculty members.

The university is in the process of campus development to make space for the large body of students currently enrolled on the main campus (NTNU 2021). The work to develop modern areas is in progress. It would be beneficial if cybernetics students also may get their dedicated are to work, as Elsys students already have, ref section 3.4.3.

Whilst the department has stated relevant learning outcomes, they are not very descriptive. They may benefit from being more student-centred, just like the rest of the education. To ensure that the learning outcomes are reached, a highly functioning quality control system should also be present.

4.1.4 Threats

Endless material growth is unsustainable, and Norway needs to find alternatives to its petroleum export. We live in a globalised society, where the pressure of competition is enormous. Norway is a small country with a population that is almost insignificant on a global basis. To keep up with the competition, educated engineers must be better than their colleagues in other countries. If Norway is to continue to prosper, the engineers, and therefore the engineering education, must be excellent.

The Wold University Rankings (2021) and QS Top univerities (2021) has ranked NTNU as number 150 of engineering and technology universities worldwide. ITK may be internationally renowned, but the students rate the education as average. It seems that the largest threat for the department is that the educational methods become outdated.

Smaller-scale threats are student opposition to new curricula (see section 3.3.3), and opposition from teachers (see section 3.3.3). By predicting the threat and by preparing for them, they may be overcome, as was proven in section 3.4.3.

4.2 Cybernetics Education Through Cybernetic Principles

Cybernetics is the science of inverting the cause and effect chain to get the intended outcome, as illustrated in Figure 4.2. The intended outcome of cybernetics education is to educate competent and creative engineers that can contribute to the country's value production. It is imperative to have clear goals and have distinct strategies, and check whether the outcomes have been reached to make a robust educational system. If the education is not sufficient, it must be corrected.

According to section 3.3 it is necessary to formulate and publish clear instructional objectives. The engineering cybernetics education goals at NTNU are to educate engineers capable of meeting society's needs. The education includes a broad theoretical and practical basis within cybernetics, control and communication theory, mathematics and problem-solving.

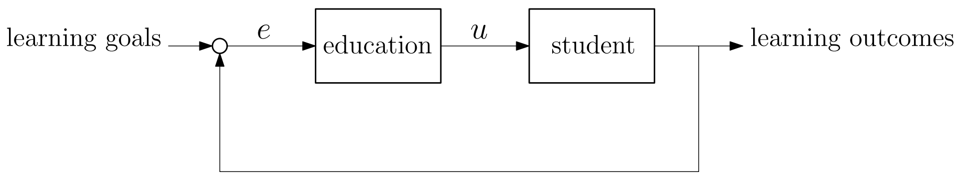

Figure 4.2: Education should be a closed-loop control system.

The graduates are also expected to have social skills, have insight into project management and become independent learners. A detailed reproduction is given in Appendix A and is not characterised by being especially clear or descriptive for students.

There is currently a gap between intended learning outcomes and actual learning outcomes at the cybernetics education provided by ITK. According to cybernetic principles, education must thus be corrected using feedback. With a basis in the current learning goals and the previous chapters, especially the ABET (2021) necessary learning outcomes for engineering programmes listed in 3.1.3, alternative learning goals are developed. The learning goals are formulated as "you", so students may use it as a guide. After the goals are formulated, some means to get to the goal are proposed. That includes feedback in the form of quality control.

4.2.1 Goals

The goal of this programme is for you to learn cybernetics, and become a proficient engineer, ready to solve local and global challenges alike. This means that you will acquire attitude, knowledge, and skills within the science. The unity is illustrated in Figure 4.3a).

Attitude is the values, motivation and inspiration that drives you to learn this science or the negative associations that stalls your learning. It is also the reason you chose to study engineering cybernetics. Knowledge (knowing that) is having facts and information, solving theoretical problems in a theoretical understanding of the science. Skills (knowing how) is the ability to do something in practice in an applied understanding of the science. Skills are not limited to building and programming robots, but also communication, teamwork and time management. As an engineer, skills are just as important as knowledge. And it is not possible to acquire either skills or knowledge without a healthy attitude.

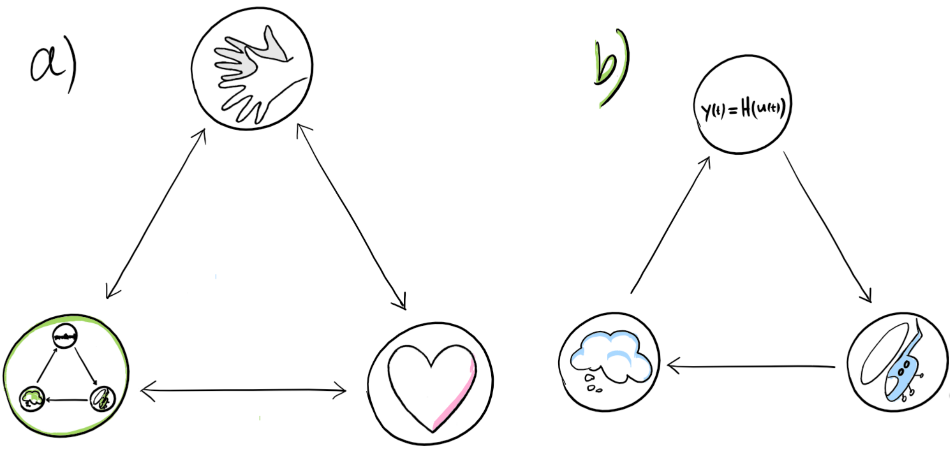

Figure 4.3: Learning triangle is a triangle (a), where knowledge includes understanding the engineering triangle (b).

Attitude: You should be aware of your attitude and how it influences your learning. Your attitude may be boosted by a sense of mastery from theoretical or practical learning activities or by social factors. The learning activities and the social environment will trigger your attitude during your learning process.

Knowledge: To gain a comprehensive understanding of the science, you should understand cybernetic behaviour in its basic form. When you know the physical and philosophical aspects of cybernetics, you will learn how to describe it mathematically so you can apply the knowledge to your preferred technical system through engineering cybernetics, as illustrated in Figure 4.3b).

This framework of mental perception, mathematical description and physical world allows you to build intuition in the science. You observe a need or an opportunity in the physical world, discover creative solutions in your mind, and observe the limitations and possibilities through mathematics. This framework goes under Knowledge in the learning triangle.

You will learn that you may apply cybernetic behaviour to any science, but that it also depends on other sciences to be described. You need physics to understand a system, statistics to estimate the past and control theory to control the future. You need ICT to implement your model in a computer, embedded systems to implement your model in a physical system and instrumentation and circuit analysis to understand how the physical system works. You need finance to know if your idea is feasible, you need project management to establish goals and meet objectives, and you need HSE to ensure a good quality workplace. These sciences are all tools for a cybernetics engineer, even though they are studied as separate subjects. Moreover, they all depend on mathematics to be described and therefore goes under Mathematics in Figure 4.3b). You will acquire in-depth knowledge within your specialisation.

Skills: This programme will prepare you for working as an engineer. Engineering fundamentals include conceiving, designing, implementing and operating to fulfil some function in real-world systems and products. You will apply your knowledge by identifying, formulating and solving open-ended problems within engineering cybernetics and robotics. You will learn to apply engineering design to produce solutions for various factors in society. You will learn to analyse existing theories, methods and interpretation and implement them into new areas within cybernetics. You will learn practical skills that prepare you for the industry.

You will learn to work independently and in multidisciplinary teams. You will learn time management, communication and other skills that are critical in a working situation. You will learn to assess and understand your work's technological, ethical, and social consequences, and you will learn to update your competence through lifelong learning.

4.2.2 Means

With a basis in the SWOT analysis and the theory presented earlier, it seems that the most significant opportunities for preparing students for working life lay in shifting to a more student-centred and active learning approach. Stronger emphasis on quality control and research-based teaching is vital in this process. Some focus points are

- Communication and cooperation
  - Between departments
  - In between teachers
  - Between teachers and students
  - Between teachers and companies
- Laboratory exercises
  - Longitudinal labwork
  - Lab-in-pocket
  - Subject centred around lab
  - Credits for student team participation
  - Participation in research or entrepreneurship

Communication and cooperation may aid the continuity and relevance of the programmes. Laboratory exercises may aid their student in applying their knowledge and becoming more prepared for a working environment. Some possible alternatives are elaborated below, but keep in mind the section 3.3.3 when implementing changes. Changing the focus from content centred to student-centred is more comprehensive and requires an attitude change in students and teachers alike.

Communication and collaboration is a natural part of engineering and research and deserves a similar status in education. The fact that IES are much better than ITK in every educational aspect (see Table 3.1), despite the departments offering similar programmes, speak volumes. The departments, especially ITK, has much to gain by communicating with their peers.

Communication and collaboration between teachers is important for development. Chapter 2 proposed an alternative way of conveying the theoretical aspect of cybernetics. The chapter has content that is split into several different subjects in the cybernetics education. At the time being, many teachers do not know what other subjects teach. This is problematic, as the students may or may not have the necessary prerequisites for the course you are teaching. To establish the relevance of course material, teachers may communicate how subjects relate to each other, guest lecture for each other and cooperate to make an engineering ladder like in section 3.4.3. There are value in peers' experience and their solutions to educational challenges; it provides an opportunity for the teachers to control the quality of their lecturing.

Where teachers do not have time, the department might hire students as assistants. This is already widely practised at NTNU, where students and PhD candidates develop laboratory exercises and assignments and assist students in solving them. Students may also be hired to assists with continuity between subjects. Teachers should also convey a sense of concern about students' learning. This is challenging in large subjects with several hundreds of participants, but IES solved this by hiring student assistants to show concern.

Cooperation with companies is also a way to go. They may sponsor laboratory exercises relevant to their work area, and they may contribute to guest lecturing and provide relevant and real-life problems for student activities. As these companies eventually will hire graduated cybernetics engineers, they might also provide valuable feedback on the intended learning outcomes of the education.

Laboratory exercises (labs) provide a way to broaden the students' understanding through active learning. It is also the best way to prepare graduates for working life situations on the mathematics presented.

It is necessary to implement abstract mathematics into practical context and physical systems to educate competent engineers. The skills are usually practised in laboratory exercises in individual subjects. The labs usually differ between the subjects, and so the student must learn and debug new equipment several times a year.

An alternative to the current lab system is a longitudinal lab. Instead of each subject responsible for equipment and lab exercises both, the department may provide one lab that suits all subjects. Thus, the subject is responsible only for the laboratory exercise. This solution will benefit students, as they will save time on learning new equipment and debugging and contribute to a continuity between subjects. As the students get familiar with the equipment, new theoretical concepts can be implemented on the familiar device, maintaining what they have learned earlier and contributing to the total understanding.

Labs that are scheduled once a week or once every two weeks have limitations. Students may only test their knowledge once at a dedicated time slot. The time must be used efficiently, so they finish before the students' dedicated time is over. It is little time for experimentation and curiosity. Also, labs often take up much space and are limited to one purpose. A lab-in-pocket that the students bring wherever. Big, fancy machines are nice, but there is an outstanding value in bringing the lab home and testing new things whenever a thought appears. The department may fund the lab-in-pocket, or it may be funded through sponsoring from companies. Alternatively, students may pay for this lab instead of textbooks like students at Elsys does. Some space-consuming labs may thus be exchanged with multipurpose areas where students can work.

Universities are usually centred around some curriculum and theory, with assignments and laboratory exercises at the side. Alternatively, the subject may be centred around an activity, with complementing theory added through lectures when needed, as in section 3.4.2. This approach is much closer to a working environment than the current practice.

Another simulation of working life is student teams on campus that build machines in their free time. These machines depend on advanced control systems and provide the students with real and valuable knowledge and skills. Some companies sponsor the most similar teams to their work and hire graduates that have attended the teams. It is possible to give students credits for joining these teams on the same level as attending theoretical subjects, like in section 3.4.1.

4.2.3 Quality Control

Quality control is an important part of education. Even though a department may develop a programme almost to perfection, it will deteriorate as time goes by, people get comfortable and lose motivation.

Communication is crucial for progress, as was mentioned as a means to obtain learning outcomes. It is also a form of personal quality control, where the individual teachers may control the quality of their lectures by comparing their practices to others. Students contribute to quality control by giving feedback to the teachers through reference groups. Whilst this system has great potential, the SWOT analysis showed that it must be improved if ITK shall provide an excellent education.

While some forms of quality control must exist, it is not simple to define good quality or excellent education. It is certainly not being up-to-date on the technology front at all times, teaching the students the newest of the newest. What is state-of-the-art today will be outdated before it is properly incorporated into the curriculum. Also, the students should not be confined by what already exists. Rather, the goal should be to provide the graduates with lifelong learning skills and the tools, not to keep up with the development of the world, but to lead it.

The first thing about cybernetics is to state a clear goal. The goal of the engineering cybernetics education may be to produce independent learners with a comprehensive understanding of cybernetic principles and equipped with a good portion of confidence, creativity and curiosity. There are several means to obtain the goal, but it not easy to formally control the actual learning outcomes. A well-functioning reference group system has great potential if it is thoroughly implemented and followed up. With a feedback loop in the educational system, it should be possible to control the educational system to produce excellent cybernetics engineers.

Chapter 5

Reflections

The scope of this thesis was to examine the education offered by the Department of Engineering Cybernetics at the NTNU and analyse how the department can offer state-of-the-art education to produce excellent engineers.

The first research question, what is cybernetics, was answered in section 2. Overly simplified, cybernetics is the science of inverting the cause and effect chain to get the desired outcome. Cybernetics establishes a fundamental way to explore the behaviour of both animate and inanimate systems and provides opportunities to further develop a range of technological and social sciences. Whilst there are other ways to derive and define the science, alternatives will not be discussed further.

The second research question, What does the literature claim about engineering higher education, was answered in chapter 3. Learning was summarised to a triangle of attitude, knowledge and skills. For graduate engineering cybernetics students to be prepared for working life, they ought to have all these three components. Whilst the literature differed greatly in methodology and quality there was a consensus that active and student-centred learning is superior to traditional teaching methods.

The two last research questions (what is the current state of engineering cybernetics education at NTNU, and which measures can be taken to optimise engineering cybernetics education at NTNU) were answered in section 4.1 and section 4.2. Whilst the department of engineering cybernetics at NTNU is globally recognised, it also has some weaknesses and related improvement potentials. The first one is communication between teachers, between teachers and students and between teachers and the industry. The second is laboratory exercises. Whilst they are already a part of most MSc programmes at NTNU, they have unexploited potential. This reflection is mostly centred around the answers found in the case.

5.1 The Need for Change

One central question has risen in the last chapter. Why is Elsys so much better than Cyb in every educational aspect? Three out of four subjects are the same in the first three semesters, and they also share subjects in later years. The students experience the same psychosocial factors. The departments are located in the same building. This is as close as we get to a controlled experiment, and the difference must mean that the pedagogical layout of the programme is somehow different.

With ITK's neighbours achieving so much, it should be possible for the programmes to cooperate. But Elsys was built from the bottom with the student in the centre, and fundamental changes are necessary to achieve the same with cybernetics. Changes in the very attitude of the teachers and the entire programme structure is necessary to achieve the same results as Elsys.

But why change a system that works? The department produces excellent research. Companies are generally satisfied with the graduates. The students are generally satisfied with their education. But despite an enormous change in the rest of the society, where everything is subject to competition following globalisation and effective use of resources, the higher-education institutions have stagnated. Computers have made their entrance, but they are used as blackboards and notebooks, not living up to their potential. The system does not work anymore.

The department's strong national and international position is well deserved. But their reputation may decline due to lack of maintenance. The lectures have continued like they always have, and whilst they may have provided the most efficient way to learn before textbooks were common, the entire 3 shows that it is not the case at the moment. It seems that all resources at ITK go to research, and everything that can continue as before will continue as before. Their international position may decline if measures are not taken.

There are certainly some programmes that are wonderfully creative and innovative, like Elsys. However, these are a minority. Departments mostly stay well within their comfort zone, teaching with the mindset of "Lecturing was good enough for me, then it is good enough for them". This mentality does not allow for progress. And whilst there are teachers at every department that do an excellent job in engaging their students, the individuals have little power over the tradition of the system.

An argument for continuing the education like before is that the students are already pressed on time. A student-centred approach may be much more time consuming, and the student will probably rebel if their workload is increased. However, this is not a sustainable argument because the information transmission method currently employed is insufficient to educate the engineers we need in our society! Change just for the change is not the answer, but to stay just because it works is also wrong. Elsys has not only managed a student-centred approach on a large MSc programme, but they have also excelled in doing so, gaining admirable feedback. The results speak in favour of a student-centred approach with active learning.

5.2 The Road to Change

Talking about change is easier than implementing it. Adding to the challenge, the means to change are not all that clear. Pedagogy includes a fair lot of guesswork and best-practice solutions, and what works on one situation will not necessarily work on another situation. Whenever humans and social sciences are added to a system, the uncertainties increase drastically. But like any cybernetic system, a clear and realistic goal is the first step. Then it may be necessary with some guesswork, combined with a solid quality control system and routines for correcting the education.

There is not much us in reflecting on which teaching technique is best. The pedagogy chapter did a thorough job of informing about opportunities and challenges. Further research into techniques that ITK are interested in implementing is up to the department to conduct.

The largest challenge remains. There is a need for an attitude change. The students must be in the centre rather than the content. To obtain this, teachers must prioritise teaching as well as research. And communication must become a natural part of the educational process, both in between teachers and between departments. Elsys seem to have overcome most of their challenges, and Cyb might learn from their peers.

Chapter 6

Conclusion

This thesis has analysed the education offered by the Department of Engineering Cybernetics (ITK) at the Norwegian University of Science and Technology (NTNU). The results show that education centred around the students and activities that promote learning produces more proficient engineers than the traditional education methods centred around a curriculum. The balance between research and teaching at ITK needs to be shifted in favour of education to obtain the goals. Changing the focus along these line requires an attitude change in teachers and students alike. It may be that the programme must be completely restructured and be built anew, or it may suffice to improve certain aspects of the education. Two specific opportunities for improvement were found to be communication and laboratory exercises. Better communication between teachers, students, and companies that hire graduated cybernetics engineers may provide students with more coherent and relevant knowledge. Optimising laboratory exercises may increase the students' overall skill, resulting in more proficient graduates. Some proposals to improved laboratory exercises are longitudinal labs across several subjects, lab-in-pocket, credits for student team participation, and open-ended real-life problems such as research and entrepreneurship. There is no blueprint to what measures are right for ITK. But by adopting the cybernetic principles and treating the programme like a closed-loop control system, correcting the education if the learning outcomes are not reached, it is possible to educate excellent engineers.

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Appendix A

Master program, 5-year, Trondheim – Cybernetics and robotics

This section is retrieved from the official web page of the study program (ITK 2021a) and translated to English.

Learning outcomes
A student who has completed the program is expected to have achieved the following learning outcomes, defined in knowledge, skills and general competence:

General competence
The study program Cybernetics and robotics will provide a broad technological basis with theoretical and practical knowledge in monitoring and control of dynamic systems. Central disciplines are control technology, automation, embedded computer systems, instrumentation and industrial computer technology.

The education shall provide knowledge and skills to participate actively in developing current and future business, and it provides a proper basis for demanding duties. The education has a methodological basis that gives the student flexibility and adaptability in a changing labour market.

Knowledge

- has broad and solid basic knowledge in mathematics, ICT and engineering

- has advanced knowledge in cybernetics, including control theory, automation, instrumentation and ICT for industrial applications
- has insight into finance, project management and HSE
- has in-depth knowledge of cybernetics' scientific and professional theory and methods
- can analyse academic issues based on cybernetics' traditions, uniqueness and place in society
- has in-depth knowledge within the chosen specialisation in cybernetics

Skills

- can independently apply knowledge in new areas within cybernetics
- can analyse existing theories, methods and interpretations within cybernetics
- has practical skills in implementing industrial solutions

General competence

- can communicate effectively with other disciplines and be able to effectively acquire competence and understanding to be able to solve tasks in new areas
- can work independently in multidisciplinary groups and collaborate effectively with specialists from other disciplines
- can assess and understand the technological, ethical and social consequences of their own work
- can actively update their own competence through lifelong learning