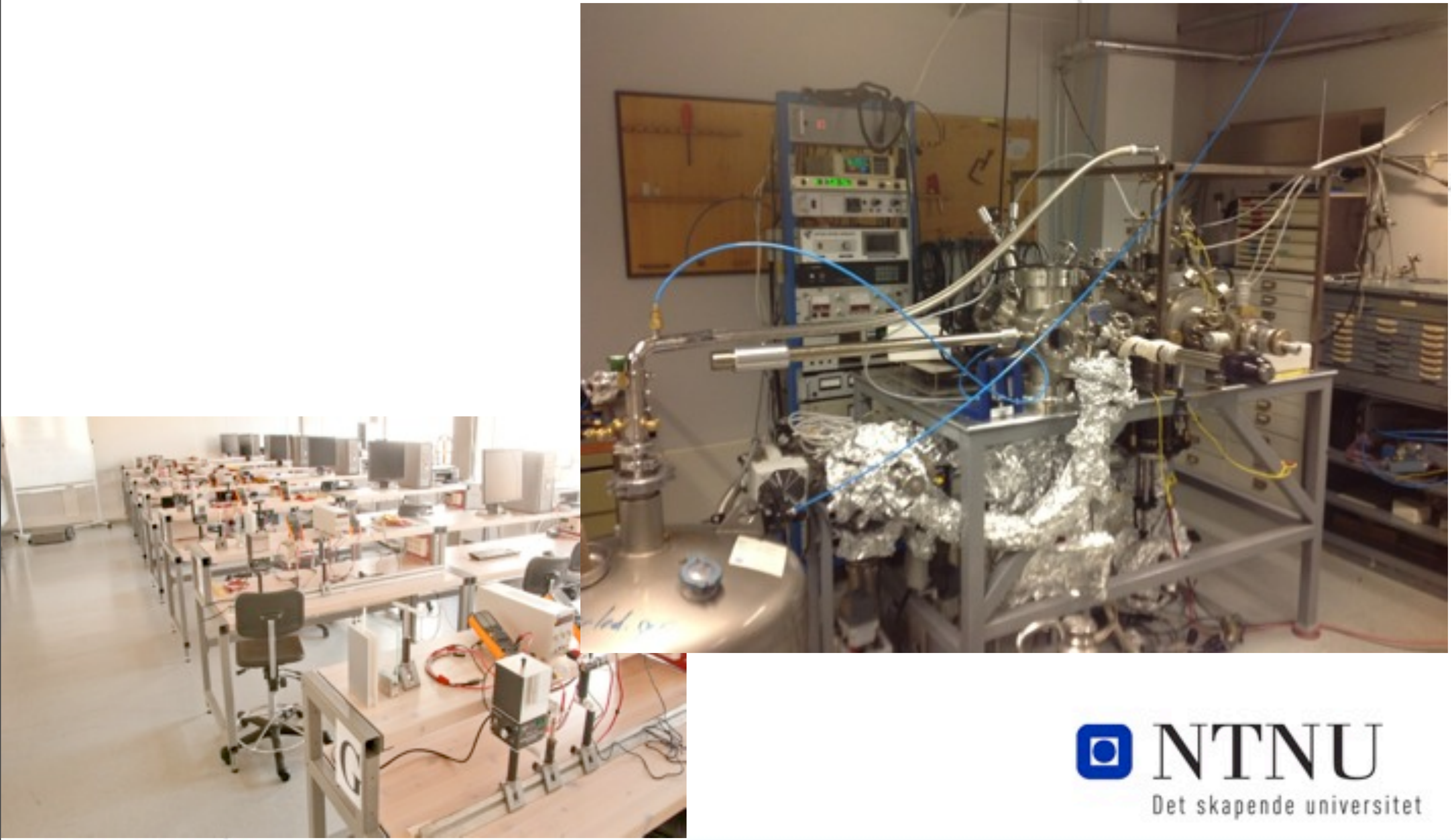
TFY4120

- Trening i eksperimentelt arbeid
- Demonstrere fysiske fenomener
- Opplæring i usikkerhetsanalyse og rapportskriving

NTNU
Det skapende universitet

Fysikklab



Fysikklab

Grunnleggande labarbeid og feilanalyse er det samme !!

Hvordan får man mest ut av en labb?

Hvordan får man mest ut av en labb?

- Arbeide igjenom materialet innen labben, få forståelse for fysikken innen oppgaven.
    - Forhåndsoppgave
- Forstå laboppstellningen, undersøk fysikken med eksperiment:
    - Abeide roligt, Deloppgaver
    - Assistenter
    - Journalføring
- Forstå usikkerhet:
    - Krever ingående forståelse av fysikk og matematisk analyse

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3 obligatoriske oppgaver runt viktige fenomen:

1. Foroppgave i usikkerhetsanalyse
   - Viskositet i glyserol (Rom C3-101, C3-107 og C3-113)
2. Mekaniske svingesystemer (Rom C4-110)
3. Motstand, kondensator og spole (Rom C3-101)
4. Magnetisk felt og flux (Rom C4-104)

Oppgavetekster lastes ned fra labens hjemmesider:

Merk: Oppgavetekstene inneholder forhåndsoppgaver som skal være utført og innført i studentenes egne lab-journaler før man møter på laboratoriet.

NTNU Norges teknisk-naturvitenskapelige universitet

INSTITUTT FOR FYSIKK

TFY4104_lab Fysikk, laboratoriekurs

OPPGAVER

	Mandag	Tirsdag	Onsdag	Torsdag	Fredag
8	TFY4115	TFY4104	TFY4115	TFY4106	
9					
10					TFY4108
11					
12	TFY4104	TFY4106	TFY4106	TFY4108	
13					
14					
15					
16	TFY4120	TFY4115	TFY4104	TFY4120	
17					
18					
19					

Fravær:

Studentene avtaler med veileder om bytte/ny tid.

Oppsamlingsøkter i slutten av labperioden.

Lab fra innen:

Lab Innen samme kurs skall vare registrert.

Lab fra TFY4102-TFY4125 kan ofte tilgoderegnes, kontakte mig

Frivillig ekstraarbeid i forbindelse med rapport:

Sjekk med veileder på den økten du ønsker å komme.

Ekstra økter organiseres i slutten av labperioden

Gjennomføring av lab-økt:

- Samarbeider i team på 2. Typisk 8 team i en gruppe.
- Lab'en varer i 4 timer (med avbrudd for spisepause).
- Det er ikke et krav om at alle punktene i oppgaveteksten skal uføres! Målet er forståelse og kvalitet.
- HMS-reglemang må føljes!
- Ordensregler for laboratoriet finner dere på web-sidene.

Eksperiment

- HMS
- Rasjonell planlegging
  - Initiera
  - Analysera/optimera
  - Gjenomfør
  - Dubbelkolla
- Dokumentasjon
  - Spårbarhet
  - Minne
  - Overblick

Laboratoriejournal:

- Føres av hver enkelt student etterhvert som arbeidet utføres.
- Bok eller hefte. A4 med stive permer anbefales (må kjøpes inn før første oppmøte).
- Alle måledata og vesentlige forsøksbetingelser føres inn.
  - Ex. vis , navn, tid dato, uppsett, mål, metode
- Svar på spørsmål i oppgavetekst.
- Forhåndsoppgaver innført før oppmøte.
- Ikke vitenskapelig rapport, men gi fullstendig grunnlag for en.
- Journal leveres veileder for retting etter lab. Rettes og leveres innen 1 uke. Rettelser of tilføyninger skal være utført av student til neste lab.

Rapport:

Skriv utfyllende rapport, fritt valg mellom oppg. 2, 3 eller 4.

Team kan levere felles rapport. Skriv da i forordet hvem som har skrevet hva.

Rapporten skal:

- Være øvelse i å skrive vitenskapelig rapport.
- Være skrevet på PC, inkludere figurer.
- Inneholde noe kvantitativ usikkerhetsanalyse.
- Være utfyllende.

PHYSICAL REVIEW B 74, 214405 (2006)

Magnetization damping in ultrathin polycrystalline Co films: Evidence for nonlocal effects

J-M. L. Beaujour, J. H. Lee, and A. D. Kent
Department of Physics, New York University, 4 Washington Place, New York, New York 10003, USA

K. Krycka and C-C. Kao
Brookhaven National Laboratory, Upton, New York 11973, USA

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The magnetic properties and magnetization dynamics of polycrystalline ultrathin Co layers were investigated using a broadband ferromagnetic resonance technique at room temperature. A variable-thickness ($1\ \mathrm{nm} \leqslant t \leqslant 10\ \mathrm{nm}$) Co layer is sandwiched between 10-nm-thick Cu layers (10 nm Cu|t Co|10 nm Cu), while materials in contact with the Cu outer interfaces are varied to determine their influence on the magnetization damping. The resonance field and the linewidth were studied for in-plane magnetic fields in field-swept experiments at a fixed frequency, from 4 to 25 GHz. The Co layers have a lower magnetization density than the bulk and an interface contribution to the magnetic anisotropy normal to the film plane. The Gilbert damping, as determined from the frequency dependence of the linewidth, increases with decreasing Co layer thickness for films with outer Pt layers. This enhancement is not observed in structures without Pt layers. The result can be understood in terms of a nonlocal contribution to the damping due to spin pumping from Co through the Cu layer and spin relaxation in Pt layers. Pt layers just 1.5 nm thick are found to be sufficient to enhance the damping and thus act as efficient "spin sinks." In structures with Pt outer layers, this nonlocal contribution to the damping becomes predominant when the Co layer is thinner than 4 nm.

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I. INTRODUCTION

The magnetization dynamics of ultrathin magnetic layers (<10 nm) is of great scientific and technological interest, as such layers are widely used in spin-injection and transport studies as well as in magnetic devices. There has been particular interest in nonlocal effects whereby layers separated from a magnetic layer influence its magnetization dynamics through nonmagnetic (NM) metallic contact layers—i.e., via conduction electrons. Such effects were modeled and studied in the late 1970s by Silsbee *et al.*[1] More recently, a scattering theory approach has been employed to describe the enhancement of the damping.[2,3] There have also been experiments[4-6] which indicate quantitative agreement with this theory based on interface parameters that can be determined from *ab initio* calculations[7] as well as transport experiments.[8]

The current interest in this mechanism is at least threefold. First, it is a fundamental mechanism of damping that can provide important information on interface and bulk spin diffusion. Second, the effect is known to play an important role in current-induced magnetization excitations in spin-transfer devices.[9] In such devices, a few-nanometer-thick magnetic layer is embedded between NM layers which separate it from a thick ferromagnetic layer that sets the spin polarization of the current.[10] The threshold current density for magnetic excitations is proportional to the damping.[11] In order to understand the physics of spin transfer, it is therefore important to investigate the effect of adjacent NM layers on the magnetic relaxation of ultrathin films. Finally, from a technological point of view, this process provides a way to engineer the damping, which is important for high-speed magnetoelectronic devices.

Mizukami *et al.* studied the Gilbert damping of sputtered NM|t Py|NM films as a function of the FM layer thickness ($2 \leqslant t \leqslant 10$ nm) and for different adjacent nonmagnetic metals NM=Cu, Pd, and Pt using an X-band ferromagnetic resonance (FMR) technique.[4] The damping was found to be consistent with the spin pumping picture: increasing with decreasing Py thickness for the films with NM=Pt and Pd only. Further, the magnetization damping of Cu|Py|L Cu|Pt structures as a function of Cu layer thickness L and with fixed Py thickness showed evidence for a nonlocal effect. However, the nonlocal damping has been studied mainly in NM|t FM|NM structures as a function of the FM layer thickness and varying the material directly in contact with the FM layer.[4,6] There have also been no experimental studies of polycrystalline Co layers, which are widely used in spin-transfer devices.

In this paper, we report systematic studies of the thickness dependence of the linewidth and Gilbert damping of ultrathin Co layers in ||y_1 Pt|Cu|t Co|Cu|y_2 Pt|| structures. The thickness of the Cu layers in contact with Co is kept fixed at 10 nm, which is chosen to be less than the spin-diffusion length in Cu. The Pt layers have no direct interface with the FM layer. The structure is modified by removing one or both of the Pt layers (y_1 or $y_2=0$). The observation of changes in the Gilbert damping confirms the nonlocal nature of this damping mechanism, and the data allow for a quantitative analysis of the interface spin-mixing conductances in the scattering theory approach.

The paper is organized as follows. In Sec. II, the film fabrication and the FMR setup are described. Section III explains the method of analysis of the resonance field and linewidth. In Sec. IV, the resonance field and the effective demagnetization field are studied as a function of Co layer thickness. The FMR linewidth and the Gilbert damping data are presented. This is followed by a discussion of the dependence of the Gilbert damping on the Co layer thickness for

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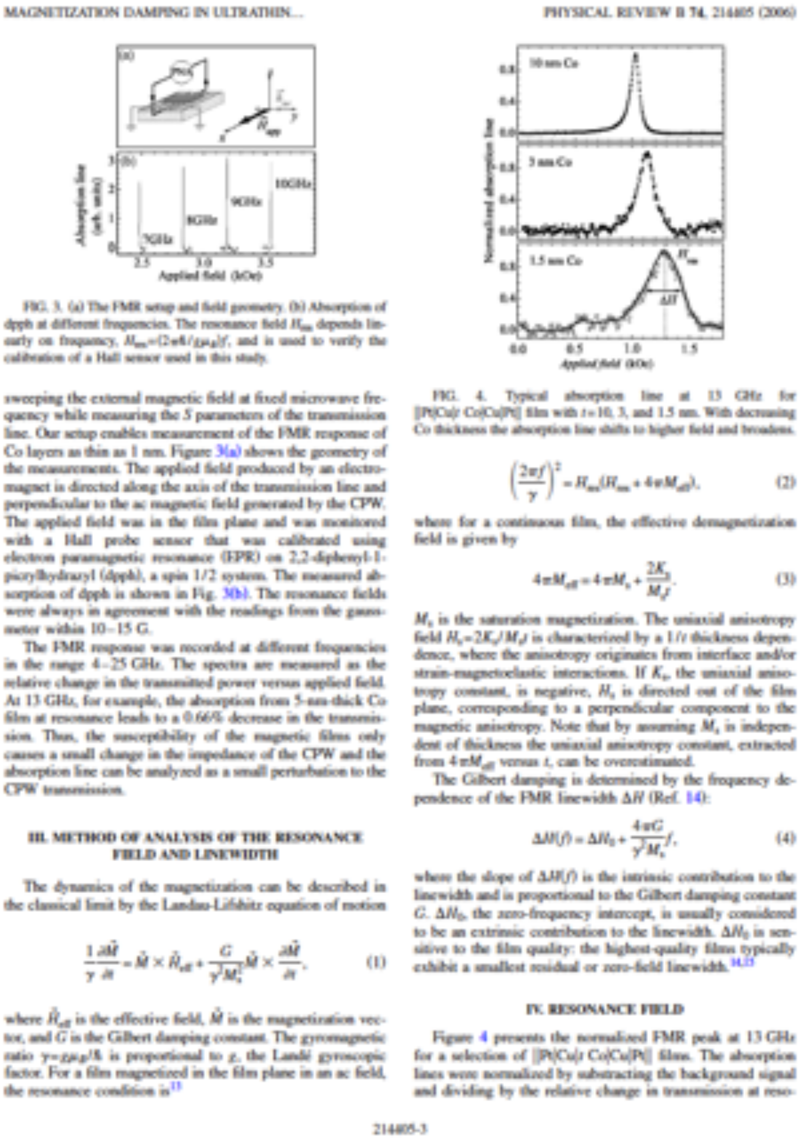


FIG. 3. (a) The FMR setup and field geometry. (b) Absorption of dpph at different frequencies. The resonance field H_{res} depends linearly on frequency, $H_{res}=(2\pi\hbar/g\mu_B)f$, and is used to verify the calibration of a Hall sensor used in this study.

sweeping the external magnetic field at fixed microwave frequency while measuring the S parameters of the transmission line. Our setup enables measurement of the FMR response of Co layers as thin as 1 nm. Figure 3(a) shows the geometry of the measurements. The applied field produced by an electromagnet is directed along the axis of the transmission line and perpendicular to the ac magnetic field generated by the CPW. The applied field was in the film plane and was monitored with a Hall probe sensor that was calibrated using electron paramagnetic resonance (EPR) on 2,2-diphenyl-1-picrylhydrazyl (dpph), a spin 1/2 system. The measured absorption of dpph is shown in Fig. 3(b). The resonance fields were always in agreement with the readings from the gaussmeter within 10–15 G.

The FMR response was recorded at different frequencies in the range 4–25 GHz. The spectra are measured as the relative change in the transmitted power versus applied field. At 13 GHz, for example, the absorption from 5-nm-thick Co film at resonance leads to a 0.66% decrease in the transmission. Thus, the susceptibility of the magnetic films only causes a small change in the impedance of the CPW and the absorption line can be analyzed as a small perturbation to the CPW transmission.

III. METHOD OF ANALYSIS OF THE RESONANCE FIELD AND LINEWIDTH

The dynamics of the magnetization can be described in the classical limit by the Landau-Lifshitz equation of motion

$$\frac{1}{\gamma}\frac{\partial \vec{M}}{\partial t} = \vec{M} \times \vec{H}_{eff} + \frac{G}{\gamma^2 M_s^2}\vec{M} \times \frac{\partial \vec{M}}{\partial t}, \qquad (1)$$

where $\vec{H}_{eff}$ is the effective field, $\vec{M}$ is the magnetization vector, and G is the Gilbert damping constant. The gyromagnetic ratio $\gamma = g\mu_B/\hbar$ is proportional to g, the Landé gyroscopic factor. For a film magnetized in the film plane in an ac field, the resonance condition is[13]

FIG. 4. Typical absorption line at 13 GHz for ||Pt|Cu|t Co|Cu|Pt|| film with $t=10$, 3, and 1.5 nm. With decreasing Co thickness the absorption line shifts to higher field and broadens.

$$\left(\frac{2\pi f}{\gamma}\right)^2 = H_{res}(H_{res} + 4\pi M_{eff}), \qquad (2)$$

where for a continuous film, the effective demagnetization field is given by

$$4\pi M_{eff} = 4\pi M_s + \frac{2K_s}{M_s t}. \qquad (3)$$

M_s is the saturation magnetization. The uniaxial anisotropy field $H_s=2K_s/M_s t$ is characterized by a $1/t$ thickness dependence, where the anisotropy originates from interface and/or strain-magnetoelastic interactions. If K_s, the uniaxial anisotropy constant, is negative, H_s is directed out of the film plane, corresponding to a perpendicular component to the magnetic anisotropy. Note that by assuming M_s is independent of thickness the uniaxial anisotropy constant, extracted from $4\pi M_{eff}$ versus t, can be overestimated.

The Gilbert damping is determined by the frequency dependence of the FMR linewidth ΔH (Ref. 14):

$$\Delta H(f) = \Delta H_0 + \frac{4\pi G}{\gamma^2 M_s} f, \qquad (4)$$

where the slope of $\Delta H(f)$ is the intrinsic contribution to the linewidth and is proportional to the Gilbert damping constant G. ΔH_0, the zero-frequency intercept, is usually considered to be an extrinsic contribution to the linewidth. ΔH_0 is sensitive to the film quality: the highest-quality films typically exhibit a smallest residual or zero-field linewidth.[14,15]

IV. RESONANCE FIELD

Figure 4 presents the normalized FMR peak at 13 GHz for a selection of ||Pt|Cu|t Co|Cu|Pt|| films. The absorption lines were normalized by substracting the background signal and dividing by the relative change in transmission at reso-

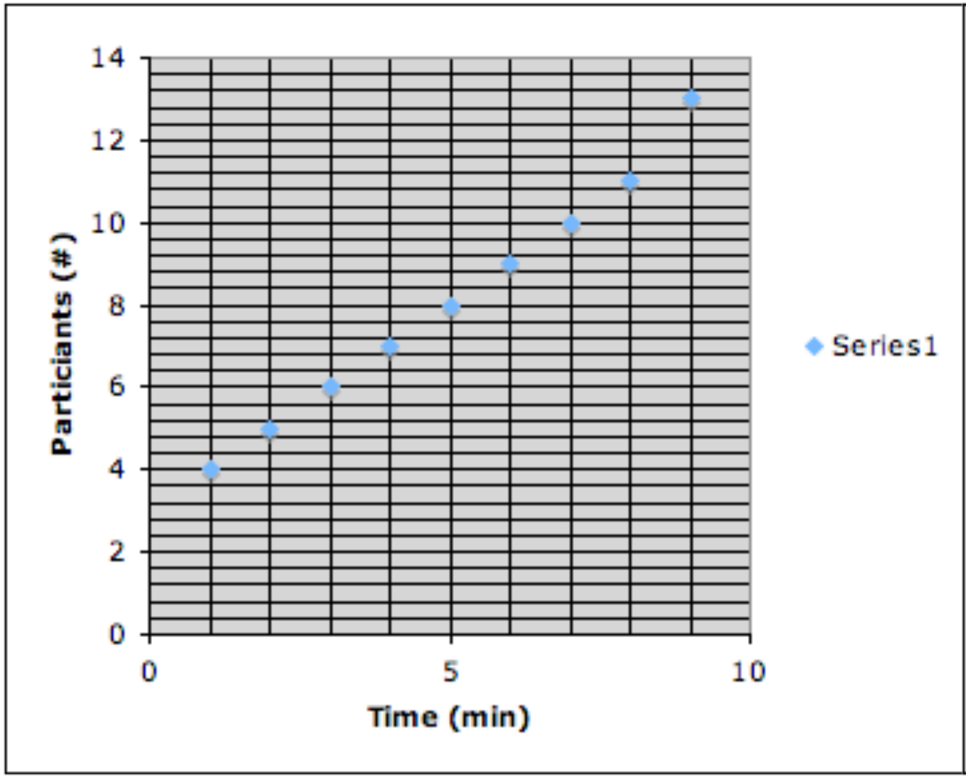
Forslag til oppbygning:

- Forord
- Sammendrag
- Innholdsfortegnelse

1. Innledning
2. Teoretisk grunnlag
3. Beskrivelse av eksperiment
4. Resultater og diskusjon
5. Konklusjon

- Litteraturhenvisninger

Figurer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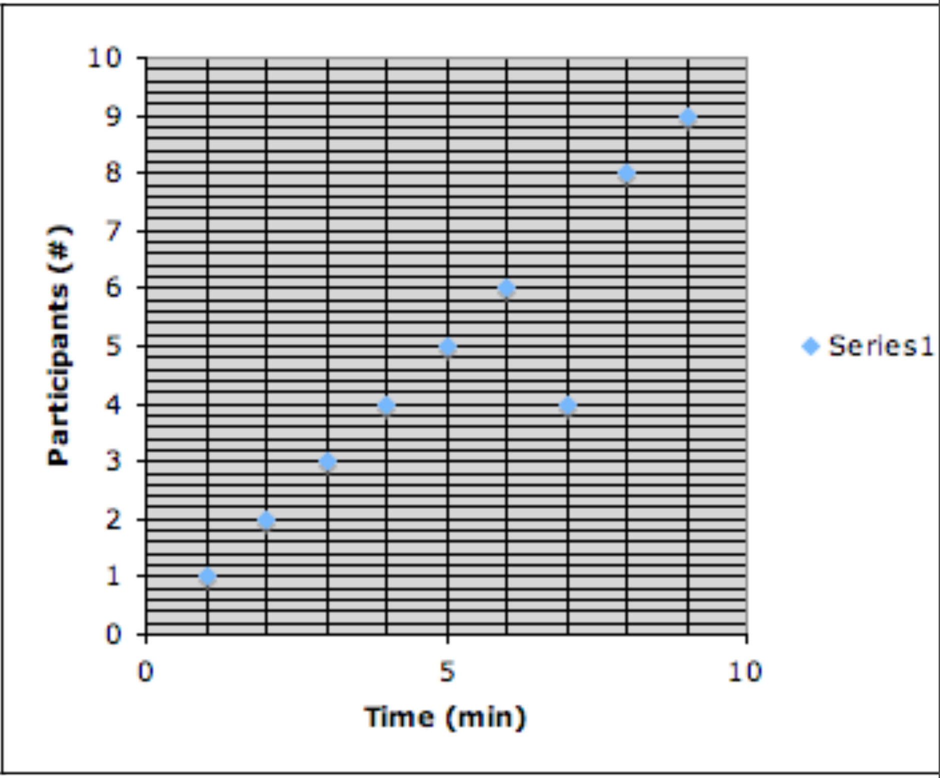
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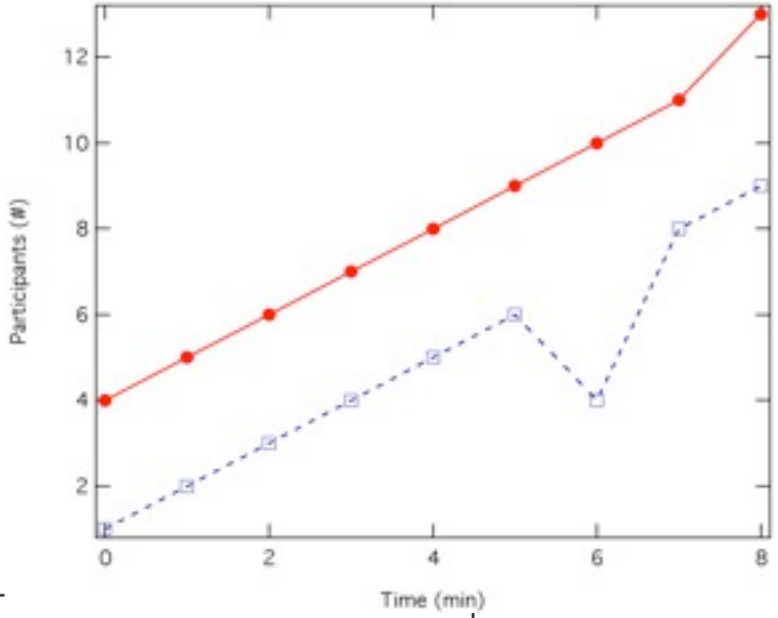
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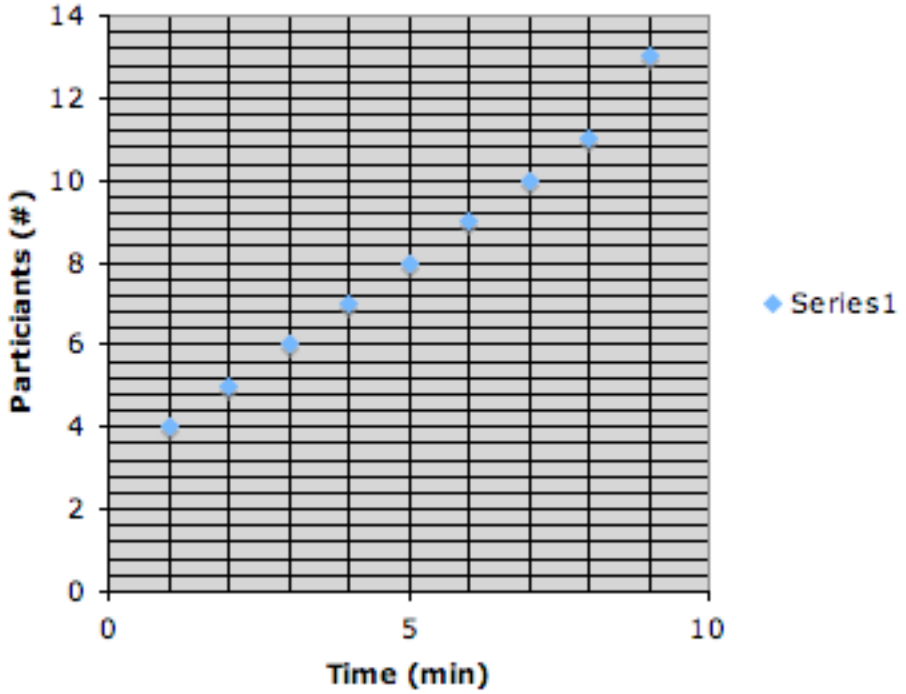
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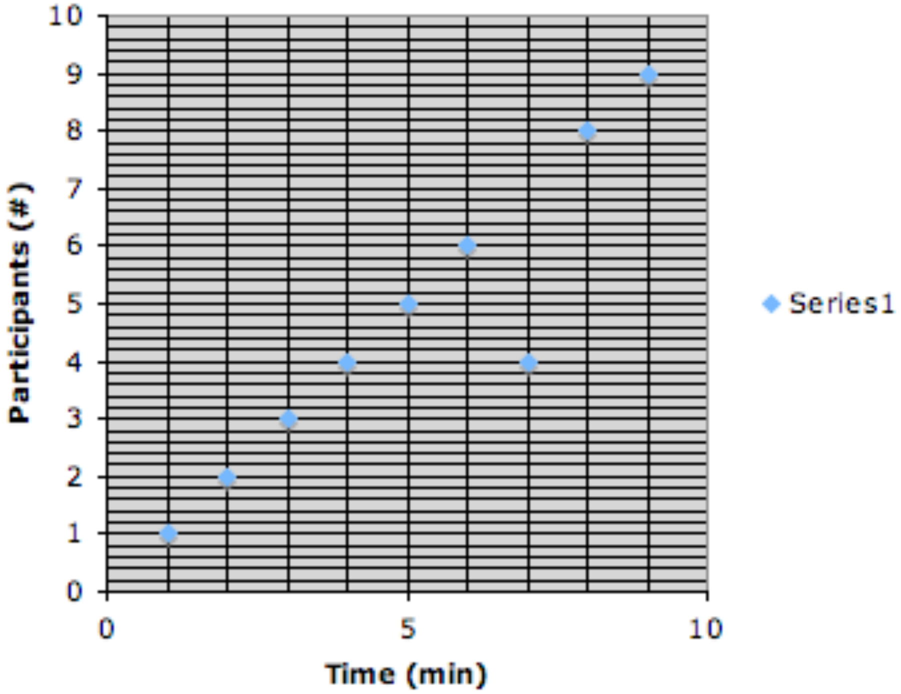
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Levering og retur av rapporter og journaler

- Rapporter - gør opp med veileder

- Journaler i korridoren i C4

Oppg. 1

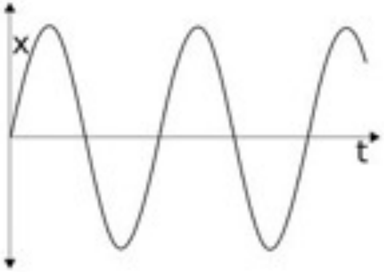
Foroppgave i usikkerhetsanalyse
- Viskositet i glyserol

Bestemme viskositet utfra fallhastighet til stålkule som synker i glyserol.

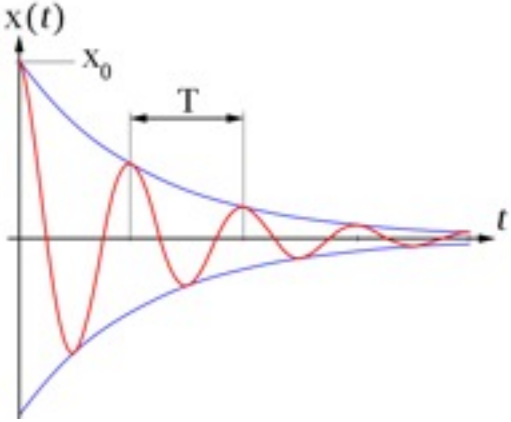
Øvelse i måleusikkerhet og feilkilder

Oppg. 2
Mekaniske svingesystemer

- Egensvingninger



- Dempede svingninger

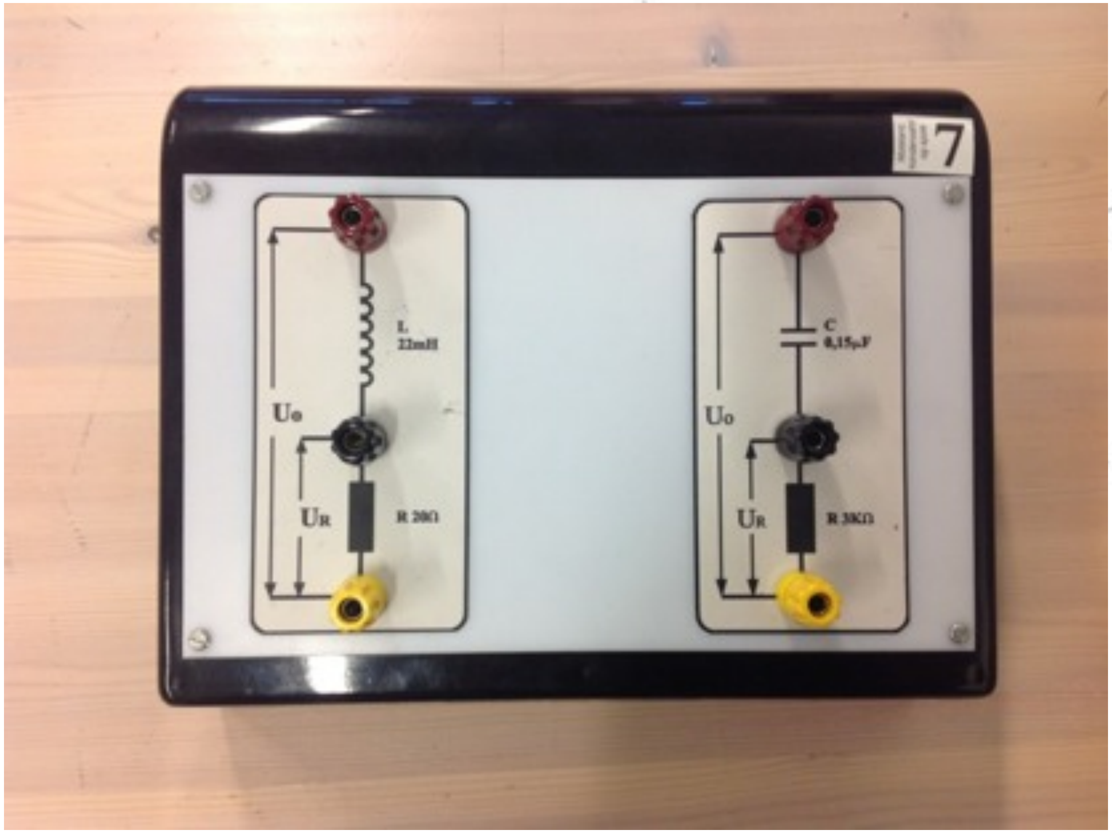


- Resonans

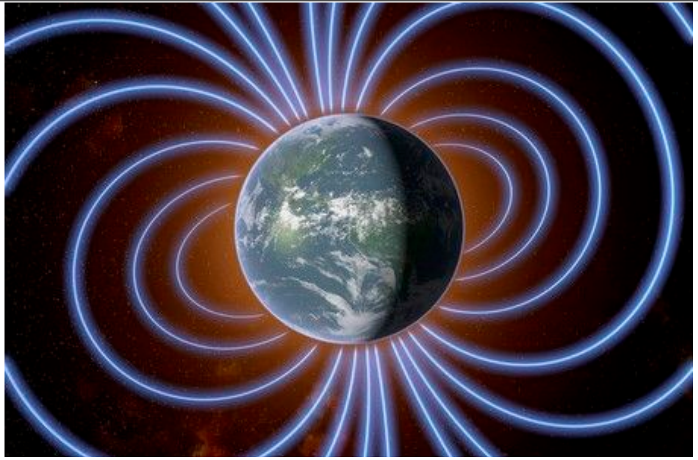
Oppg. 4
Motstand, kondensator og spole.

-Bestem C og L

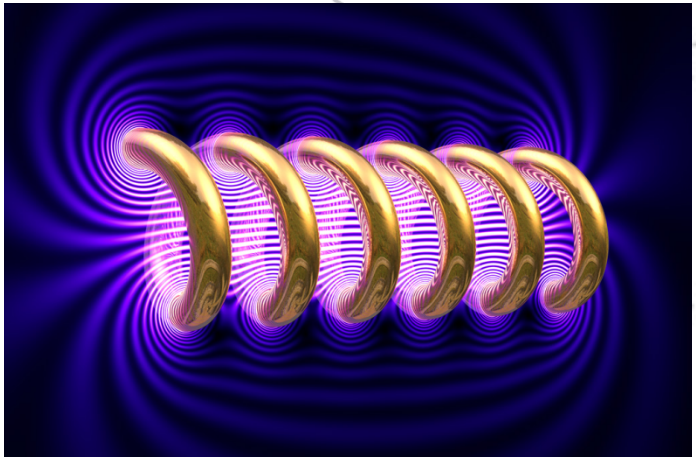
-Bestem AC karakteristikken for RC og RL kretser



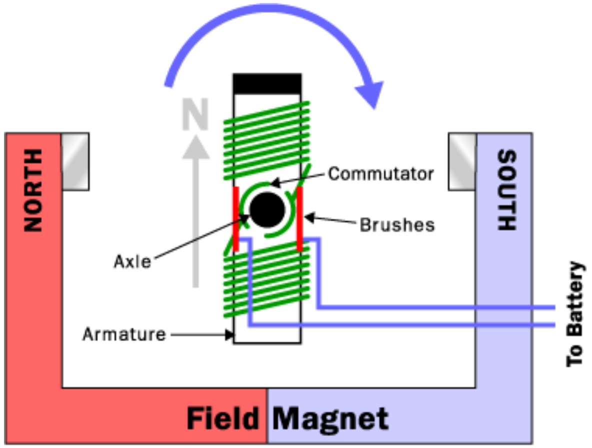
Oppg. 4
Magnetisk felt og fluks



Måle magnetfeltstyrke v.h.a. Hall-probe.



Bestemme magnetfeltet generert av strøm gjennom en spole.



Sette sammen en elektromotor.

Måleusikkerhet

Måling: tallfeste en egenskap (hvor langt, tungt, tyktflytende noe er).

Måling: Verdi og enhet   (2m,   4.5 kg,   1.2 Pa s)

Alle målinger har en viss grad av usikkerhet!

$$L = 193 \pm 2 \text{ mm}$$

Hvor stor usikkerhet vi kan tolerere avhenger av situasjonen

Standardsystemet:

- Nøyaktige målinger skjer etter kalibreringar i standardsystemet (SI)
- En kjede av kalibreringar, som lenkes tilbake til nasjonale institutt (justervesenet) og BIPM (The Bureau Internasjonal des Poids et Mesures).
- Er lenket till SI-systemet som gir enheter.
- Andre

Tre ferdigheter for estimat:

1) Estimere feil i en variabel (standardavvik)

2) Estimere hvor stort feil en feil i en variabel gir på slutresultatet
(Gauss feilfortplantningslov)

3) Estimere konstant

Kurvetilpassning

Ulike typer av feil

Grove feil:

Noterer at spenningen var 2.4 V når den egentlig var 2.4 mV

Botemiddel: Gjør dem ikke!

Definisjonsusikkerhet:

Hva er lengden til en sau?

Botemiddel: Klare og spesifiserte definisjoner.

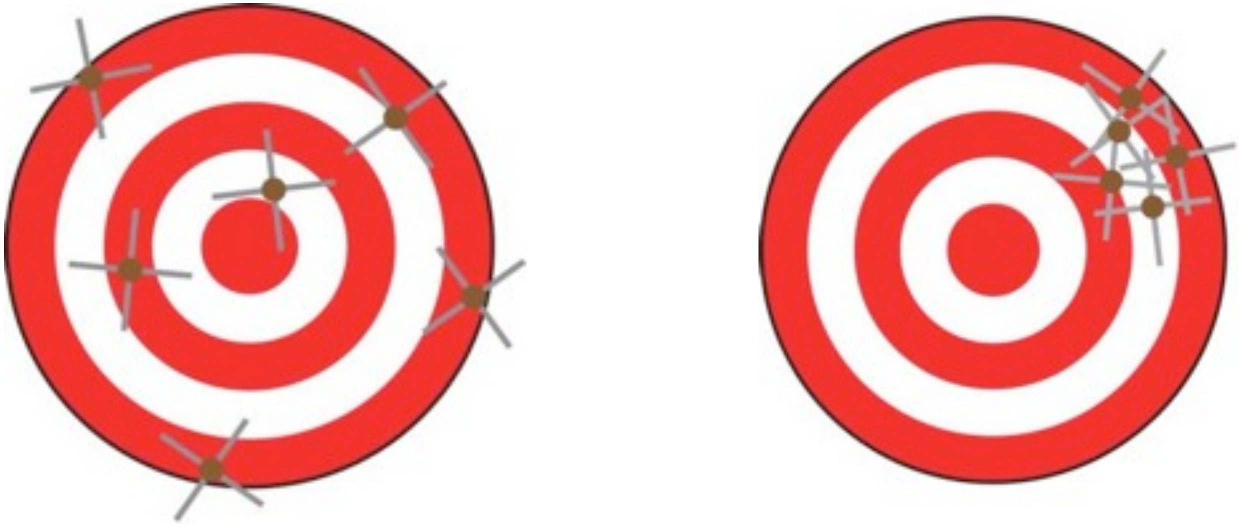
Systematiske feil:

Mer om dette snart

Statistiske feil:

Mer om dette snart

Presisjon og nøyaktighet



Presisjon og nøyaktighet

Nøyaktighet

Presisjon

Systematiske feil

Blant annet:

- Feil kalibrert måleinstrument/for tidlig måling
- Måler utenfor instrumentets tiltenkte måleområde
- Menneskelig egenskap
- Andre forsøksbetingelser enn antatt

Eksempel: Linjalen er ikke eksakt 30 cm, men 30.04 cm

Botemiddel:

- Tenk kritisk igjennom utføring av måling
- Sjekk nøyaktighet og måleområde for instrument
- Kalibrer måleutstyr
- Anslå fornuftig grense for ukorrigerbare systematiske feil

Statistisk usikkerhet

Gjentatte målinger gir forskjellige verdier

Eksempel: Vi måler lengden av et bord flere ganger.
Bruker meterstokk med fin gradering.

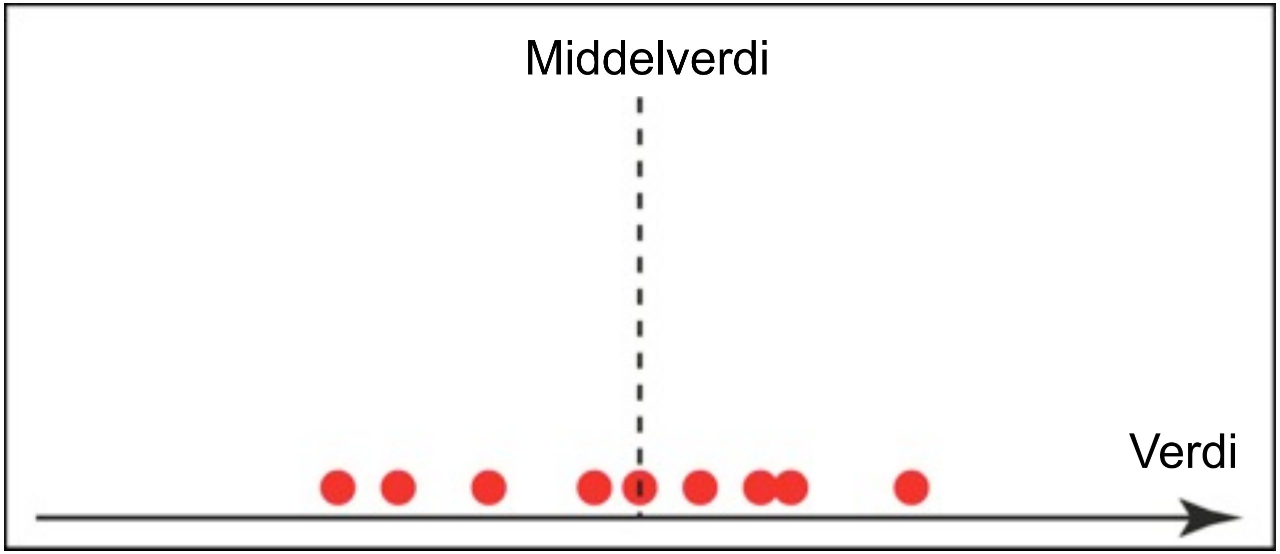
Vi får: x_1 = 3.12 m x_2 = 3.07 m x_3 = 3.10 m

Botemiddel:

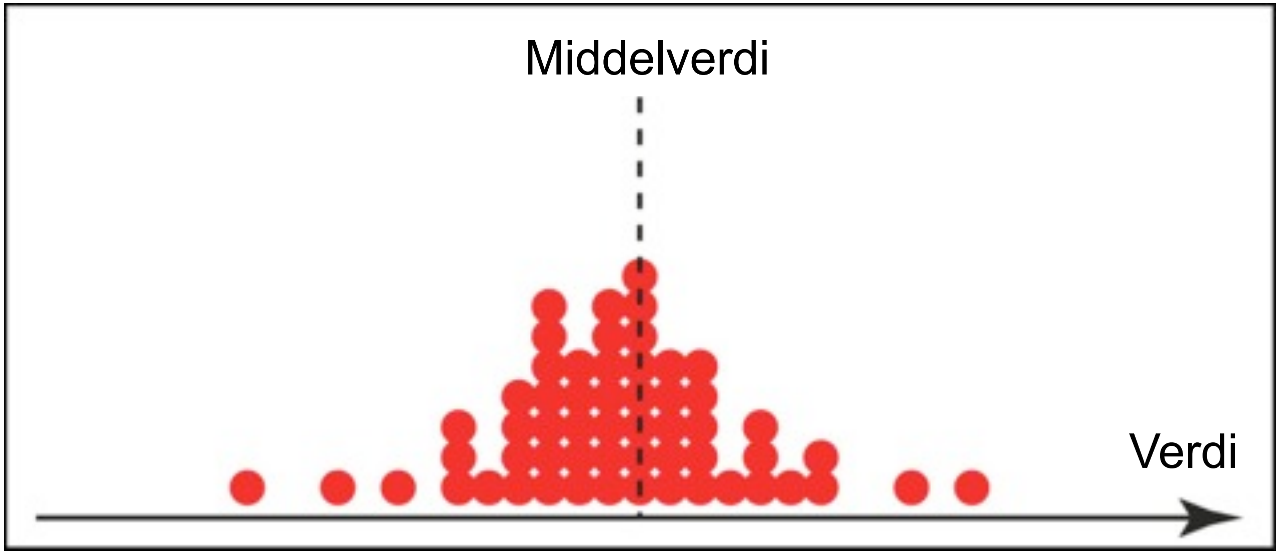
Mål mange ganger, beregn middelverdi $\overline{x}$

Variasjonen i målingene angir usikkerheten som betegnes Δx

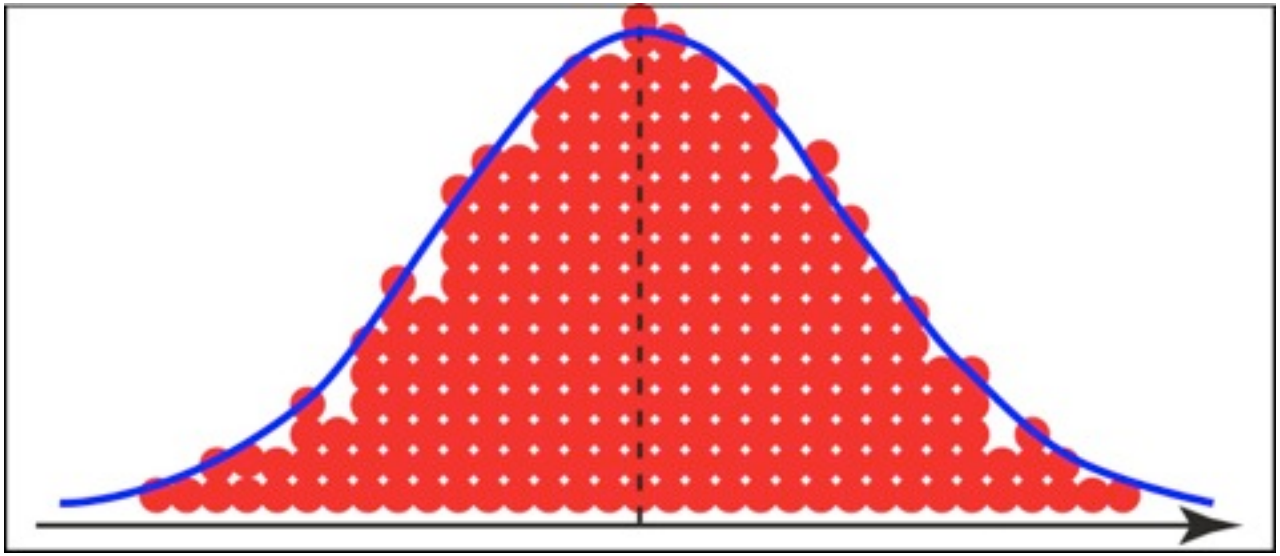
Fordelinger av målinger



Fordelinger av målinger



Fordelinger av målinger

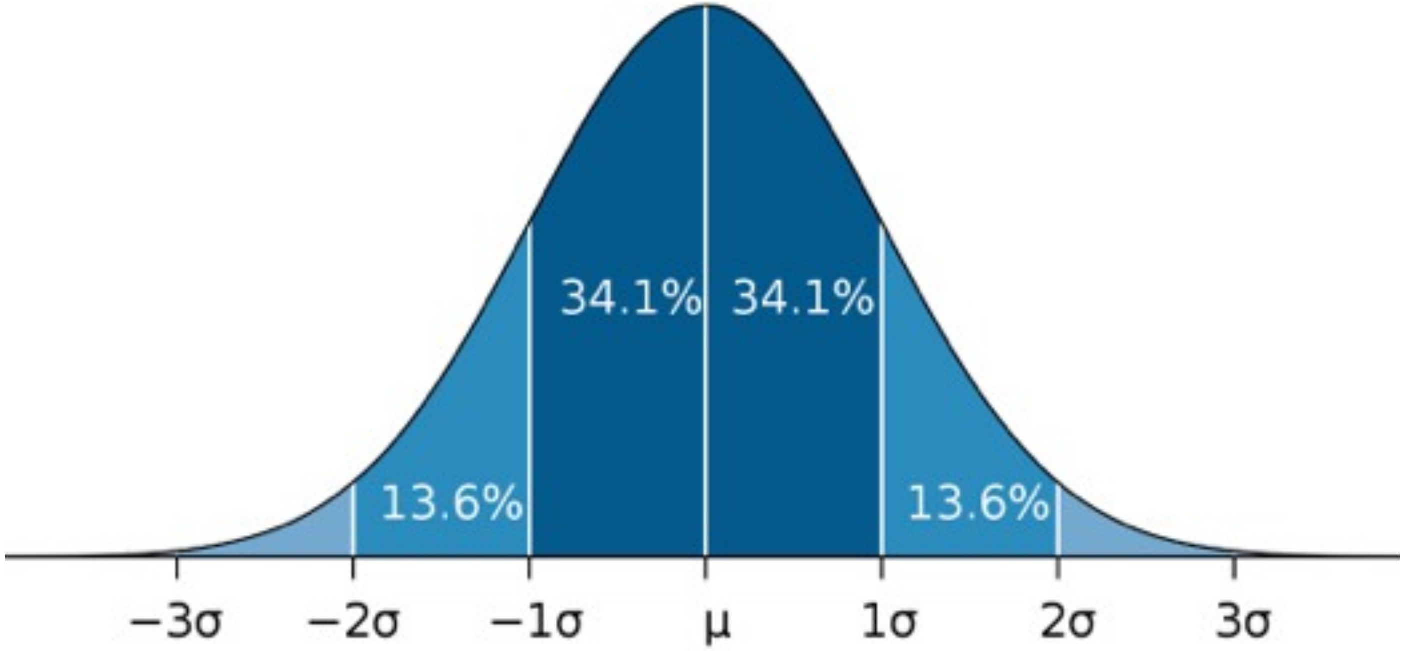


Normalfordeling

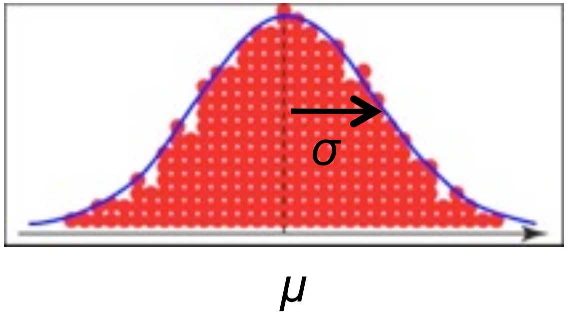
$$f(x) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

$f(x)$ = sannsynlighet for å måle verdien x
μ = middelverdi
σ = standardavvik

95% sannsynlighet ved 2 σ



Estimater for μ og σ :



Middelverdi μ estimeres med: $$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Standardavvik σ estimeres med: $$\Delta x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Usikkerhet i enkeltmåling!

Estimat for usikkerhet i middelverdi: $$\Delta\bar{x} = \frac{\Delta x}{\sqrt{n}}$$

Feilforplantning

Vi beregner en fysisk størrelse $f(x,y,z,\ldots)$ ut fra målinger av de individuelle fysiske størrelsene x, y, z, ...

Anta at x, y, z,... er uavhengige. Da er usikkerheten i f :

$$\Delta f = \left(\left(\frac{\partial f}{\partial x} \Delta x \right)^2 + \left(\frac{\partial f}{\partial y} \Delta y \right)^2 + \ldots \right)^{1/2}$$

Dersom en har målt middelverdier for x, y, z, ... bruker vi:

$$f = f(\bar{x}, \bar{y}, \bar{z}, \ldots)$$

og $\Delta\bar{x}, \Delta\bar{y}, \Delta\bar{z}, \ldots)$ i uttrykket for usikkerheten

7. Feilforplantning

Eksempel: $f(x, y, z) = \frac{3xy^2}{z^3}$

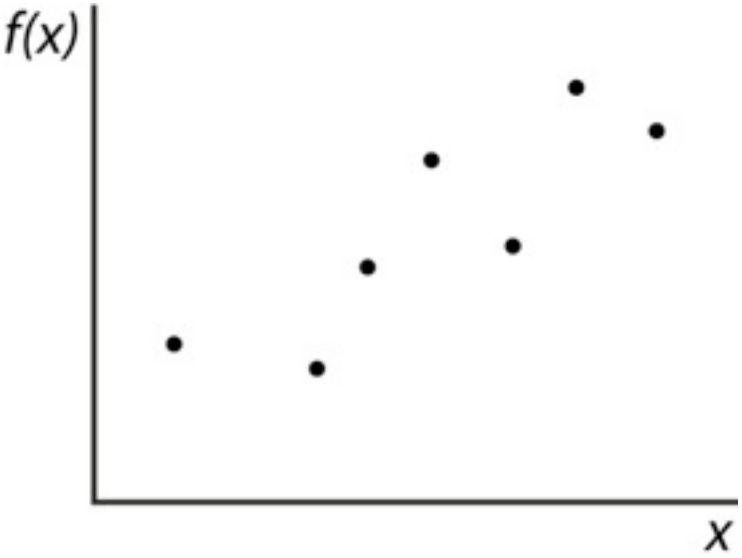
Tips: Lettere å regne med relativ usikkerhet:

$$\frac{\Delta f}{f} = \left(\left(\frac{\frac{\partial f}{\partial x} \Delta x}{f} \right)^2 + \left(\frac{\frac{\partial f}{\partial x} \Delta y}{f} \right)^2 + \ldots \right)^{1/2} -$$

Som gir: $$\frac{\Delta f}{f} = \left(\left(\frac{\Delta x}{x} \right)^2 + \left(2 \frac{\Delta y}{y} \right)^2 + \left(-3 \frac{\Delta z}{z} \right)^2 \right)^{1/2}$$

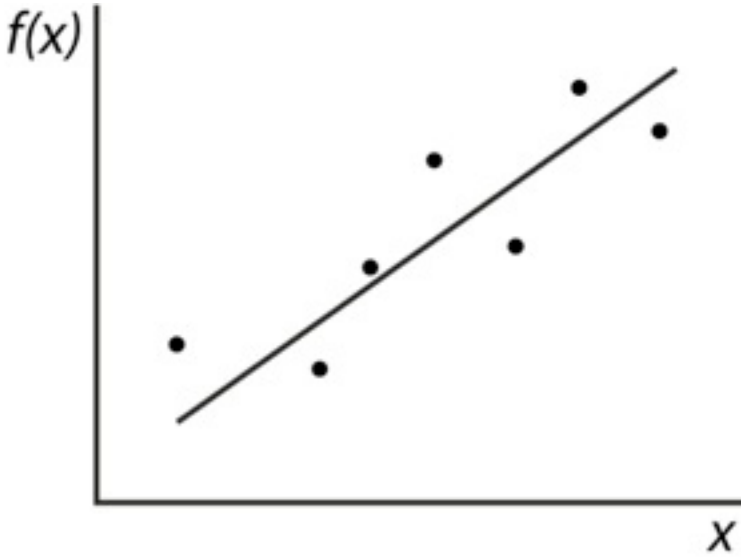
8. Kurvetilpasning

La oss si at vi tror *f* er en lineær funksjon av *x*: $f(x) = k_1 + k_2x$



8. Kurvetilpasning

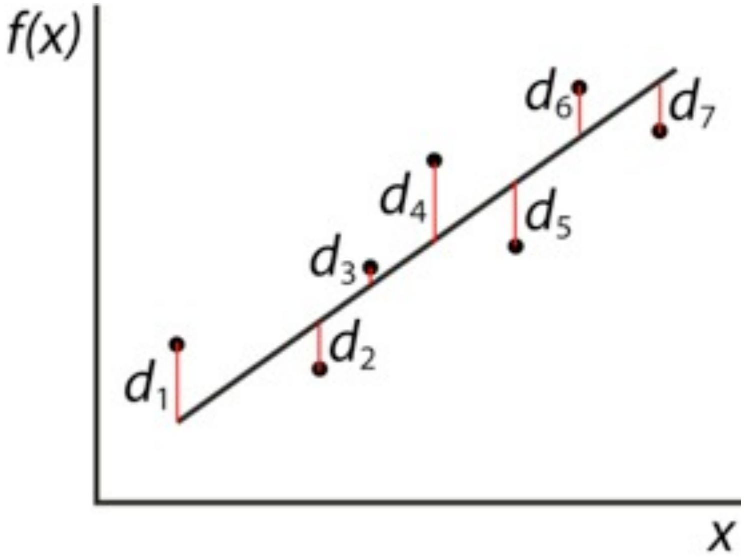
Hvordan finner vi “den beste” rette linja?



8. Kurvetilpasning

Minste kvadraters metode: Minimaliser summen av kvadratet av avvikene

$$Q = \sum_{i=1}^{n} (d_i)^2$$



Se notat om usikkerhetsanalyse på websiden for detaljer

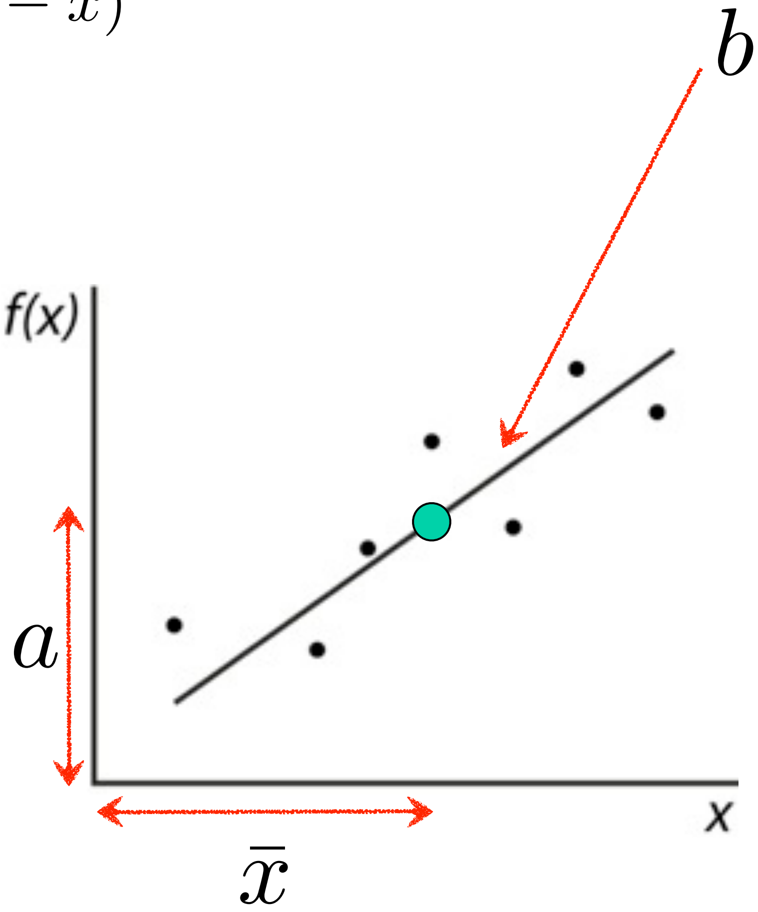
Minste kvadraters metode

$$y = k_1 + k_2 x \Rightarrow y = a + b(x - \bar{x})$$

$$Q = \sum_{i=1}^{n} \left[y_i - (a + b(x_i - \bar{x}))\right]^2$$

$$\frac{\partial Q}{\partial a} = 0$$

$$\frac{\partial Q}{\partial b} = 0$$

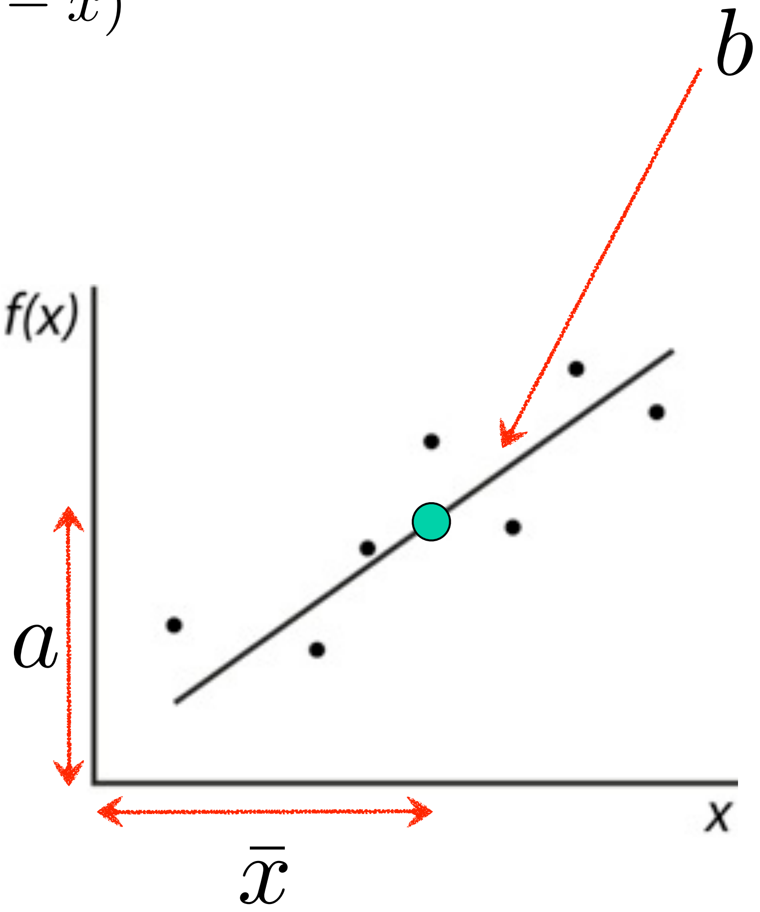


Minste kvadraters metode

$$y = k_1 + k_2 x \Rightarrow y = a + b(x - \bar{x})$$

$$a = \frac{1}{n}\sum_{i=1}^{n} y_i$$

$$b = \frac{\sum_{i=1}^{n}(y_i x_i - \bar{x}\bar{y})}{\sum_{i=1}^{n}(x_i^2 - \bar{x}^2)}$$

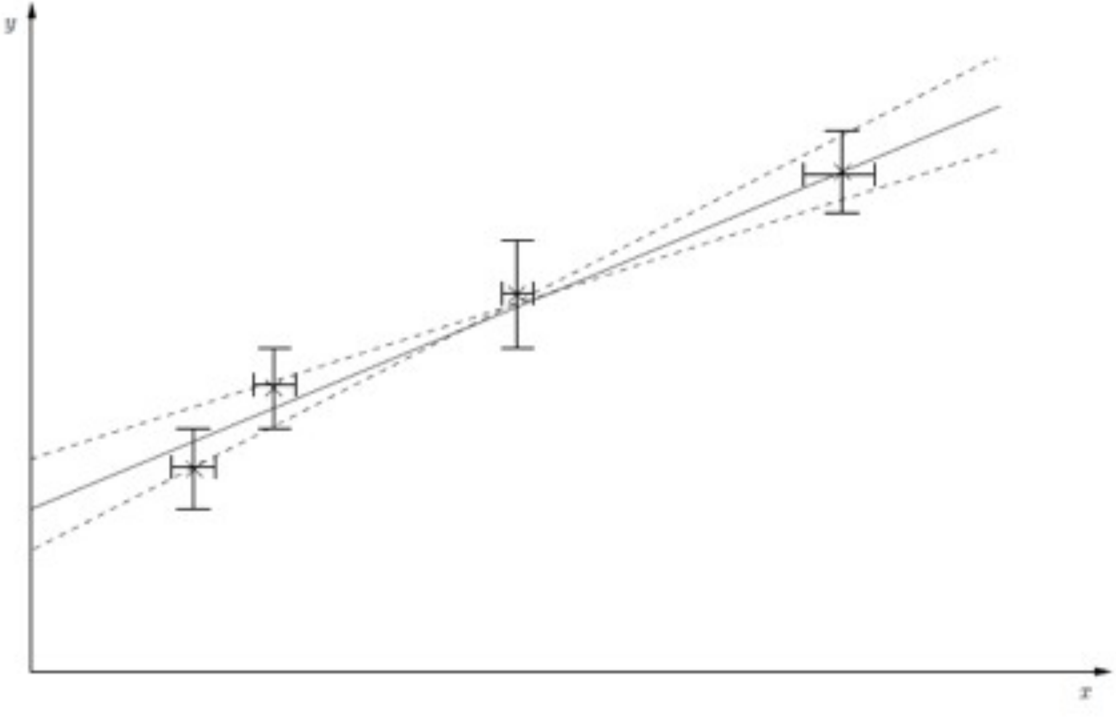


Kurvetilpasning

Advarsel: ikke stol blindt på kurvetilpasninger i software.

Inspisér data nøye: er de lineære? Er det noen datapunkter som skiller seg ut?

I noen tilfeller kan visuell kurvetilpasning gi bedre resultat.



Oppsummering

- Måledata har alltid verdi, enhet og usikkerhet.

- Redusér systematiske feil ved å tenke kritisk på utførelse av måling.

- Redusér statistisk usikkerhet ved å repetere målinger. Oppgi estimert usikkerhet.

- Måledata er ofte normalfordelt rundt middelverdien.

Middelverdi: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

Standardavvik for enkeltmåling: $\Delta x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$

Standardavvik for middelverdi: $\Delta\bar{x} = \frac{\Delta x}{\sqrt{n}}$

Feilforplantningsloven: $\Delta f = \left(\left(\frac{\partial f}{\partial x}\Delta x\right)^2 + \left(\frac{\partial f}{\partial y}\Delta y\right)^2 + \ldots\right)^{1/2}$

Velkommen til Lab!