# Education in CEM and EMC at Chalmers

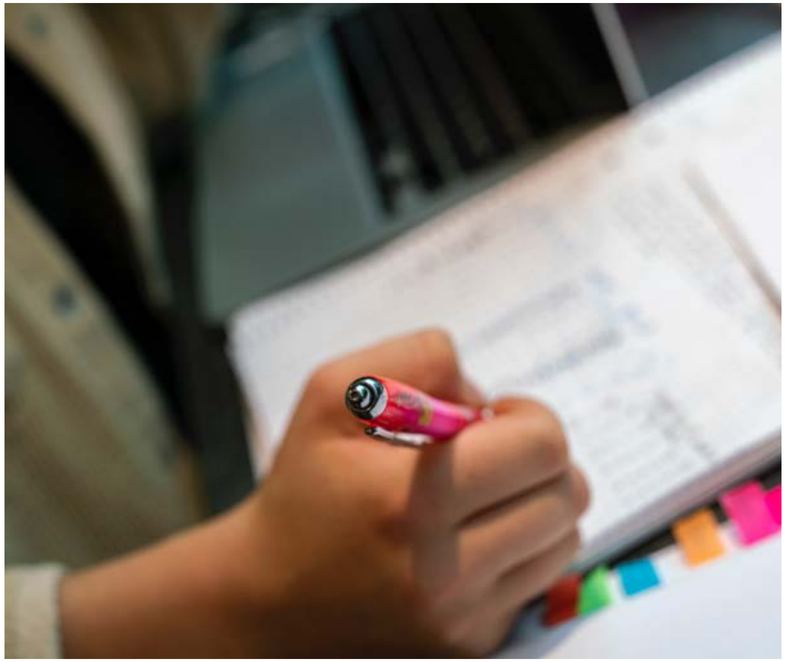
Prof. Thomas Rylander | Dept. of Electrical Engineering | 2024.10.29

# Outline

- Theme for the meeting “CEM for EMC”
- Introductory part – elaborate, compare and contrast
  - Experimental work (or lab work in EMC)
  - Theoretical work (or computational work by CEM)
- Describe two courses at Chalmers
  - SSY200 – Computational electromagnetics
  - EEN230 – Electromagnetic environment, health and compatibility
- How to sign up for courses at Chalmers

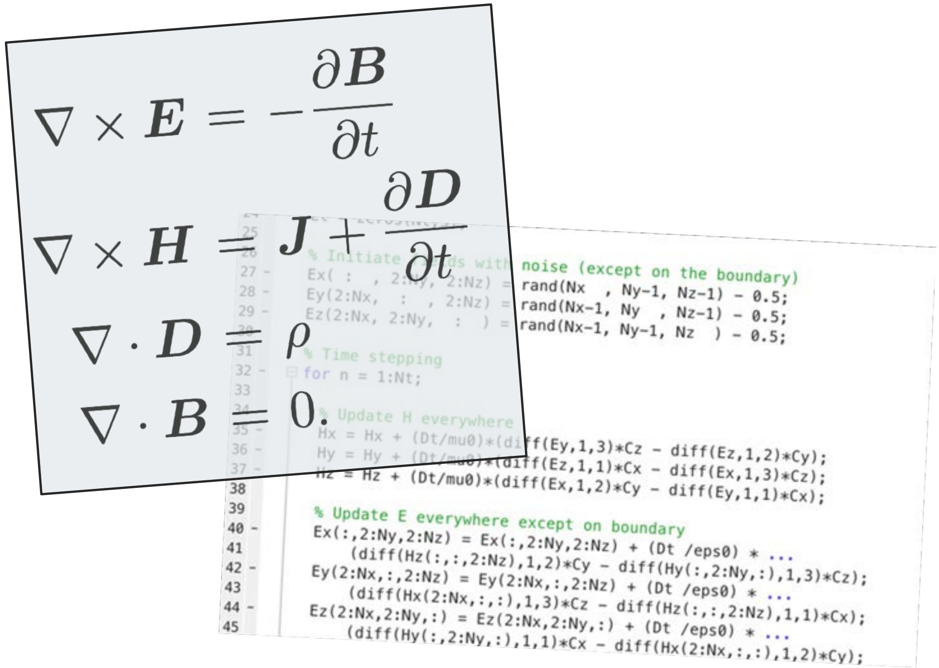
# Some comparisons between computations and experiments

- Quotes (unknown origin, to me…)
  - No one believes the computational result except the person that performed the computations (Maybe the same applies to theory as well?)
  - Everyone believes in the experimental result except the person that performed the experiment
- Some questions
  - What is right and wrong?
  - How do we know if it is right or wrong?
  - What to do when in doubt?



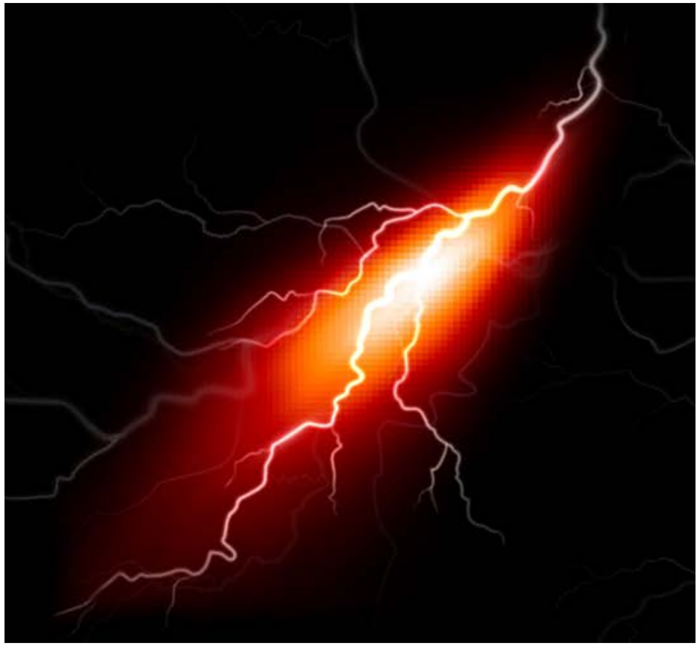
# Computational (and theoretical) work

- Every underlying circumstance/quantity in the computation can be controlled in detail
- Do the results agree with “reality”? (”reality” = experiments)
- The same result for different computations (e.g. performed different days)
- Easy to make parameter studies
- The model can be “compared with itself” to give relative results – absolute results are more difficult to get right



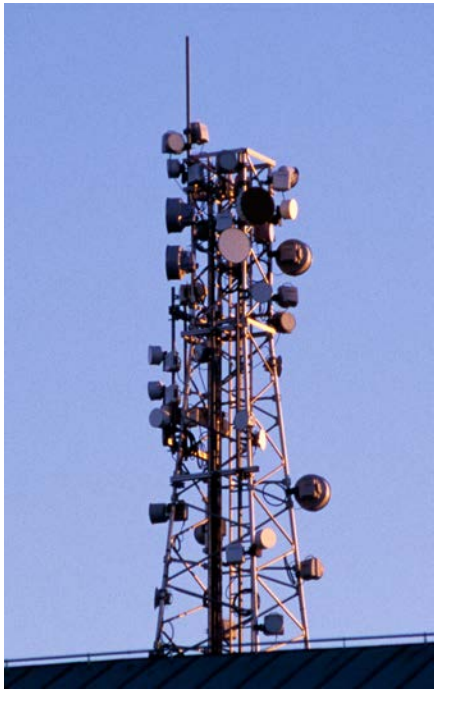
# Experimental work

- Difficult or impossible to know and control all underlying circumstances/quantities involved the experiment
- The results agree with ”reality”!
  (assume that the experiment is correctly conducted)
- Different results for “the same experiments”
  - Stochastic errors
  - Systematic errors (may drift wrt time)
- Difficult to make parameters studies for some parameters (and others very easy)



# Workflow for computational work (applies also for theoretical work)

1. Real-world problem/system/situation
   (often modified/simplified for experimental work)
2. Model the problem by physics and mathematics
   (involves simplifications)
   - Electric circuit – non-linear behavior, temperature, …
   - Maxwell's equations – geometry, materials, …
3. Calculate/compute the solution given the model
   - Analytical methods – highly limited but very informative
     - Exact answer (for a rather small number of models)
   - Numerical methods (CEM) – less limited but "only for one case"
     - Approximate answer (always…)



# Illustration of the different error contributions for quantity “q”

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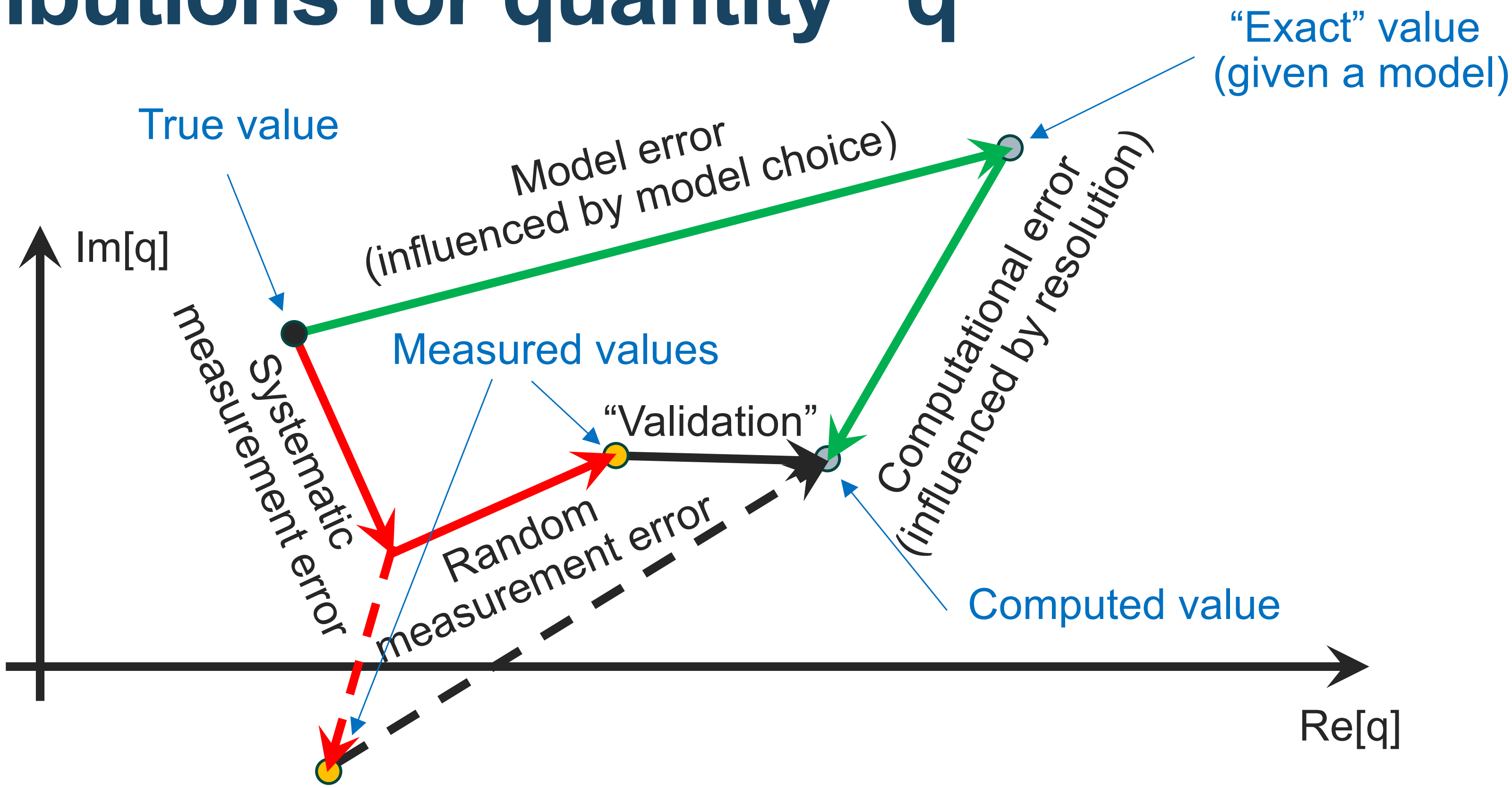
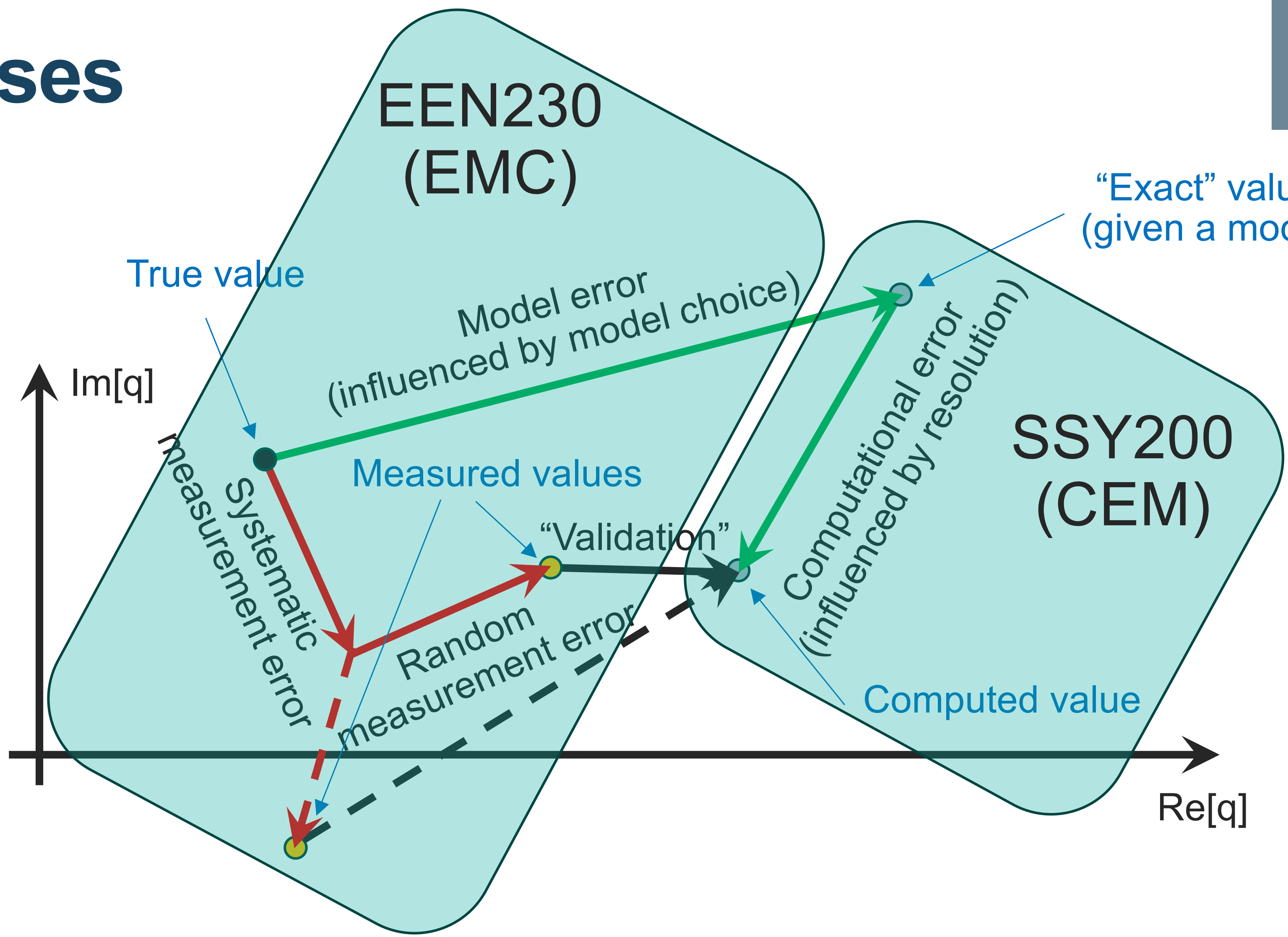


# Courses


EEN230
(EMC)
SSY200
(CEM)
Im[q]
Re[q]
True value
"Exact" value
(given a model)
Model error
(influenced by model choice)
Systematic
measurement error
Measured values
"Validation"
Random
measurement error
Computational error
(influenced by resolution)
Computed value

# Computational electromagnetics

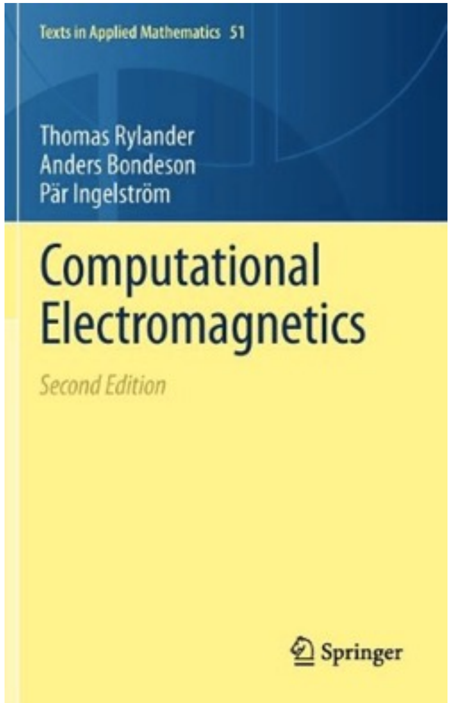
Course code: SSY200

About 15 participants per year

- MSc-students (year 4 or 5 from many programs)
- PhD-students (not only Chalmers)
- Industry

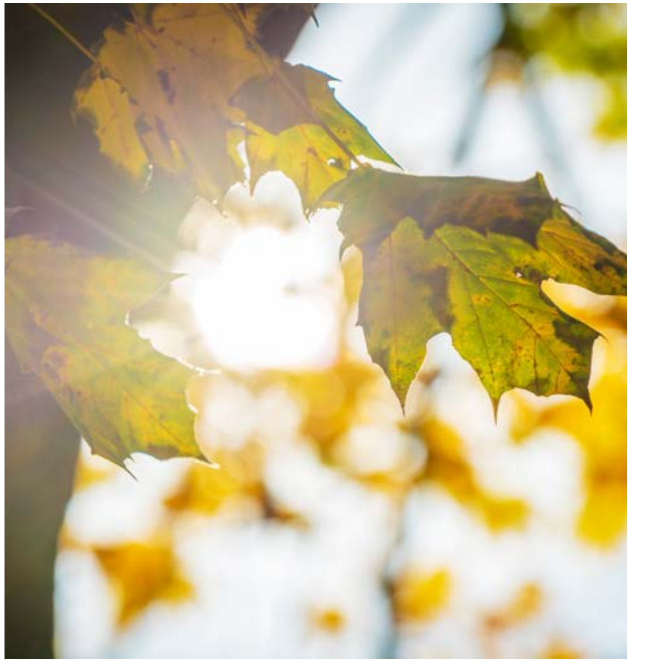
Given in study period 3
(= first half of the spring semester)

Examination: 4 hand-in assignments (one is optional) and
oral exam (7,5 credits)



# Introduction to CEM (from the course)

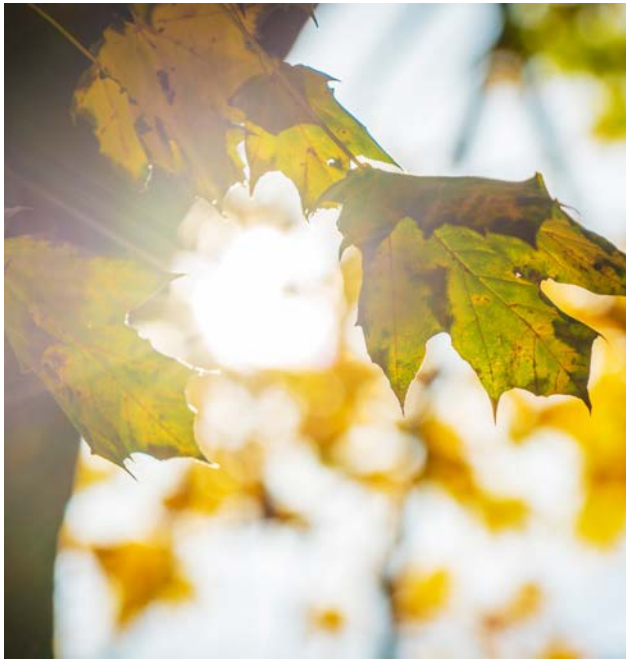
- Computers get more and more powerful but improved algorithms are equally important!
- Finite resources for computations
  - The computer has finite memory
  - The user has finite time (and energy/money/…)
- Usually, the user don’t want to wait for the results more than one week
  - feedback from the computation is needed to be able to make iterations
  - the program may crash – in particular for complicated computations
  - there may be “blunders” in terms of wrong input data, bugs or other problems



# Introduction to CEM (from the course)

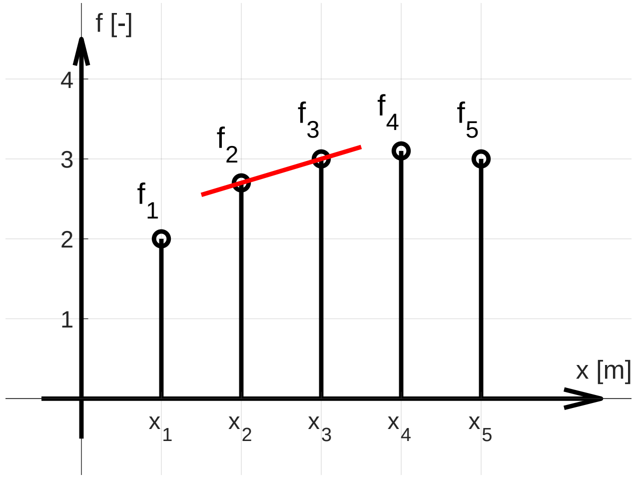
Finite resources (memory and time) impose limitations on the problems that can be solved

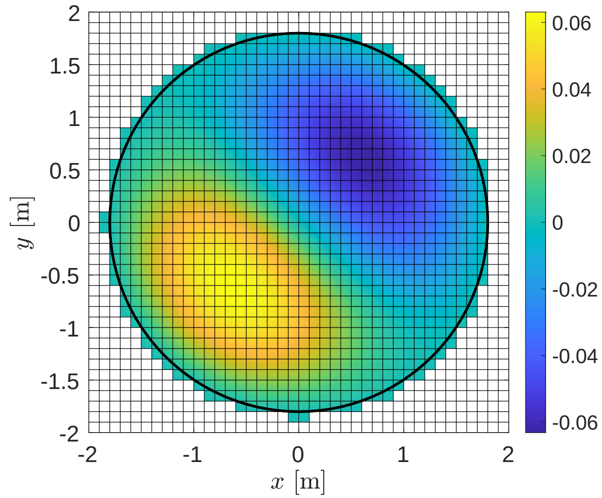
- Electromagnetic field model (with infinite number of degrees of freedom) must be limited to a finite number of degrees of freedom (use them well…)
- Implies approximate results – the exact result can never be achieved
- The approximation can be improved by increasing the resolution
  - Points per wavelength
  - Inclusion of geometrical details
  - Material variations
  - etc



# Finite-difference (FD) schemes

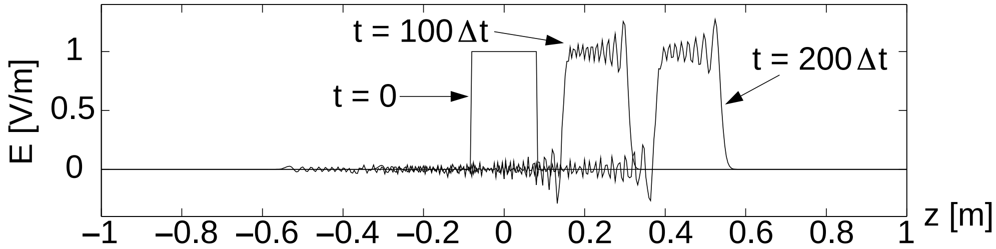
- Introduce grid points $x_i$ (uniform in space typically)
- Assume that the field f(x) takes one value $f_i$ at each grid point
  - Unknown between grid points
- Approximate derivatives with "finite-difference stencils" in differential-equations (slope of straight line…) ⇒ numerical error
- Staircase approximation (can be mitigated by cut cells)

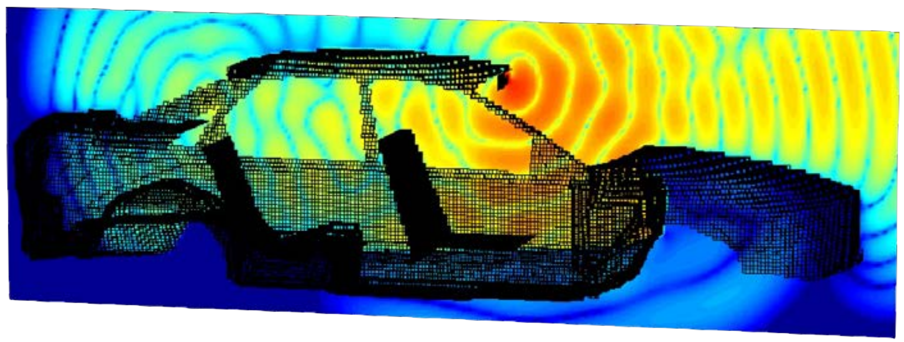


# Finite-difference (FD) schemes

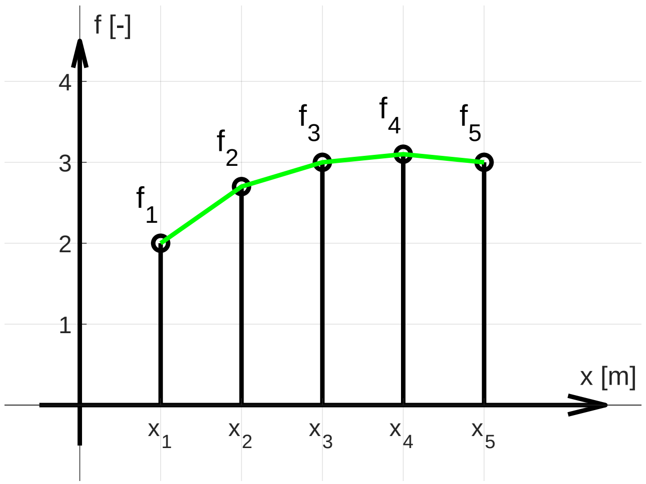
- Numerical error
  - Electromagnetic wave propagates at the wrong speed (= numerical dispersion)
- Applied to time as well – the FDTD scheme
  ⇒ Explicit time-stepping (no matrices)
  (“Courant condition” limits time step)
- Resolution “rule of thumb” – about 20 points per wavelength (small number of wavelengths)
- Double the frequency and keep the *absolute* phase error constant
  - Memory requirements increase by factor $2^{9/2} = 22.6$
  - Computational time increases by factor $2^6 = 64$

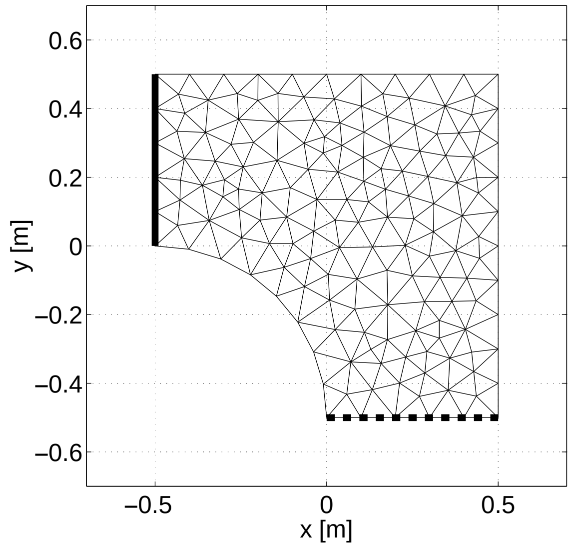


# Finite Element Method (FEM)

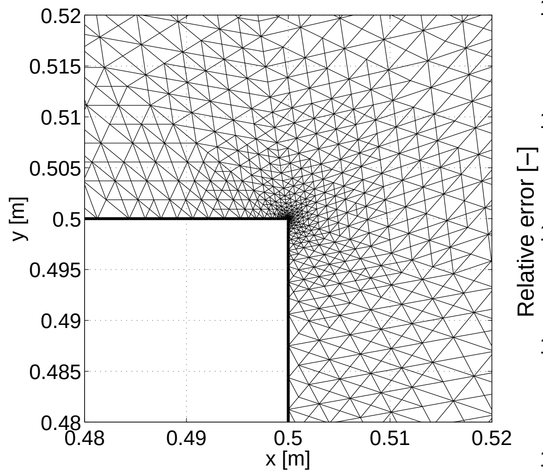
- Divide the domain into finite elements
- Assume that the field is piecewise linear inside the finite elements
  - approximate ansatz ***function***
  - numerical error
    (similar effects as for FDs)
- Derive weak form – a compromise to make the differential equation fulfilled (as good as possible…)
- Body conforming (triangles in 2d and tetrahedrons in 3d)

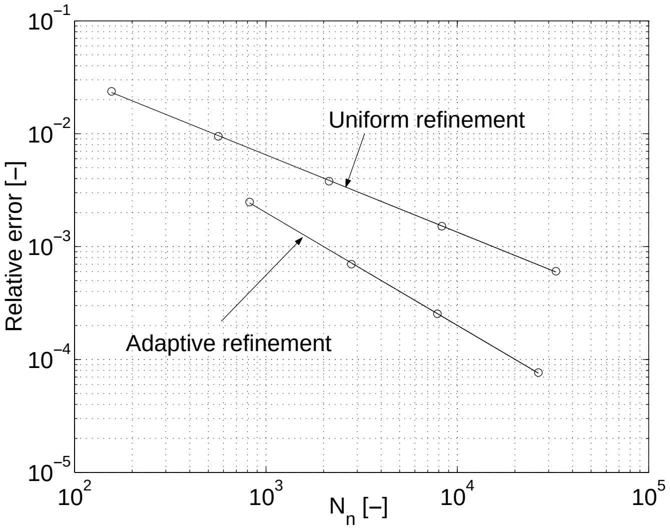


# Finite Element Method (FEM)

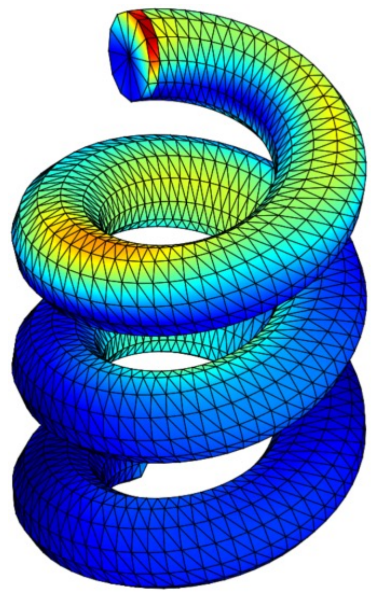
- Meshes of unstructured triangles or tetrahedra allow for
  - Complicated geometry
  - Space varying resolution and adaptive mesh refinement
- Sparse matrices
  - Direct solvers for 2d problems
  - Iterative solvers for 3d problems
- Time-domain methods
  - Work well with implicit time-stepping (no Courant condition)



# Method of Moments (MoM)

- Integral equation instead of differential equation
  - Sources (currents and charges) are the unknowns
  - Enforce boundary conditions for the electromagnetic field
  - Use the FEM to compute the sources
- Advantages
  - Good for problems with “small wires/surfaces with sources” and large volumes for the fields (free-space with infinite and homogeneous space)
  - Fast methods available (almost linear scaling with frequency)
- Drawbacks
  - Full matrices (=requires very much computer memory) for basic version
  - Difficult to evaluate the matrix elements (singularity from Green’s function)



# Electromagnetic environment, health and compatibility

Course code: EEN230

Estimated number of BSc-students per year: 50-60

- Biomedical Engineering, Year 3 (compulsory)
- Electrical Engineering, Year 3 (compulsory elective)
- Automation and Mechatronics Engineering, Year 3 (elective)

Given in study period 4
(= second half of the spring semester)

Examination: one project (1,5 credits) and written exam (6,0 credits)

# Contents overview

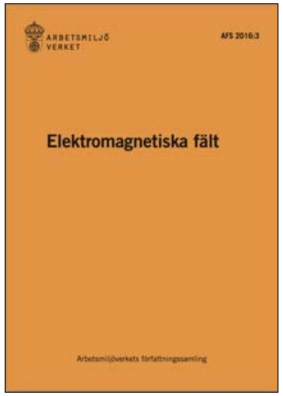
- Define environment and sustainable development
  - particular focus on electrotechnical equipment and electromagnetic fields.
- The electromagnetic environment is described in terms of different perspectives
  - electromagnetic spectrum
  - categorization of the electrotechnical equipment/system
  - sources, victims and coupling paths for electromagnetic disturbances.
- Biological effects on humans given low-frequency magnetic fields, high-frequency electromagnetic fields and ionizing radiation.


Blistered face after "facelift" based on radiofrequency treatment patented by a company – the patient suffered second-degree burns

https://www.thesun.co.uk/news/8919577/botched-facelift-blisters-burned-inside-out/

# Contents overview (cont.)

- Legal regulations and requirements in different contexts: international, EU, national and local.
  - Bettina Funk (Svensk Elstandard) gave a lecture on standardization
- Analysis, design and testing of electrotechnical equipment
  - both theory and experiment
- Possibility to participate in a study visit at a local hospital, institute or company.
- Project work.





DIRECTIVE 2014/30/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 26 February 2014

on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)

# Study visits

- RISE in Borås
  - Full anechoic chambers
  - Semi-anechoic chambers
  - Reverberation chambers (including VIRC)
- Volvo Cars Corporation
  - Semi-anechoic chambers
  - Outdoor test site under tent
- Sahlgrenska University Hospital
  - Test lab (no chambers)
  - Presentation with motivational challenges from a hospital environment

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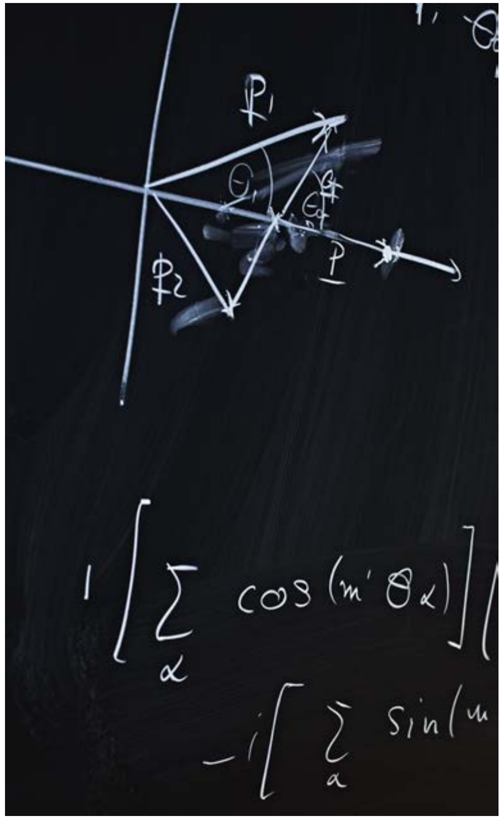
# Pedagogical challenges and approaches

- Most students did not study electromagnetic field theory
- No good book given the broad range of topics
  - Slides that present the material in a summarized manner
  - Prerecorded video lectures on electromagnetic field theory (from the pandemic)
  - Suggested reading list for in-depth studies
- Course material developed
  - Slides
  - Tutorial problems
  - Project
  - Table of formulas – no derivations based on Maxwell's equations

# Pedagogical approach and technical contents – overview

- Electromagnetic field theory
  - Review of vector analysis
  - Static phenomena based (mainly) on infinitely long line sources
  - Quasi-static phenomena – based on the static cases
  - Electromagnetic plane waves
- Transmission line theory (continuation of “line sources” from EM theory)
  - Differential-mode and common-mode currents
  - Transmission lines with $N$+1 conductors (matrices L, C, R and G)
  - Special cases – low-frequency situation and 2 conductors



# Pedagogical approach and technical contents – overview

- Filters and non-ideal component behavior
  - Review of Fourier analysis
  - Differential-mode and common-mode filters
  - Resistor, capacitor and inductor at (too) high frequencies
- Conducted emissions and susceptibility
  - Crosstalk based on transmission line theory
  - LISN
- Antennas (mainly wires)
  - Electric and magnetic (elementary) dipoles
  - Radiation characterization
  - Half-wave dipole, array antennas, antenna factor and Friis transmission formula

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# Pedagogical approach and technical contents – overview

- Radiated emissions and susceptibility
  - Based on array antennas (two parallel wires) for emissions
  - Similar model for susceptibility/immunity
- Measurements

Lectures supported by some experiments in front of the entire group of students in the lecture hall – no (physical) experiments conducted by the students themselves.

Course ends with a written exam.

# How to sign up?

You apply via universityadmissions.se or antagning.se for the spring or autumn semester:

- Deadline in October 15 for spring semester (passed for spring semester 2025…)
- Deadline in April 15 for fall semester

Send an email to me at

`rylander@chalmers.se`

to get more information.

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