INF2340 - Simulation and Visualisation

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Overview

• What is numerical simulation?
  – modeling and simulation
  – can it be of any use?
  – is it important?
  – what is the connection with computer science?
  – what are the future challenges?
• Although this will be about simulation, you will also see a lot of visualization....

What is simulation?

• Reconstruction or prediction of phenomena and processes, especially from science and engineering

• Objectives depend on concrete task:
  – Reconstruct and understand known scenarios
  – Predict unknown scenarios
  – Optimize known scenarios

• Multidisciplinary:
  – Mathematics + Informatics + Application

Behind it all: mathematics!

“Shocking” claim:
Underneath the development of modern science lurks a belief in a perfect world that can be described in a precise language. This language is mathematics...

Moreover:
Every truth we claim to possess about nature can be formulated as a mathematical statement.

And:
There is safety in numbers! By expressing our beliefs in terms of numbers we are able to quantify and qualify. Hence we can master the uncertain and wrest more knowledge from nature.

Mathematical models

• Formal abstraction of reality

• Issues when deriving a model:
  – What are the quantities of interest?
  – How do they influence each other?
  – What do we want from the model?

• Issues when analysing a model:
  – Do we have a solution, and if so – is it unique?
  – How accurate is the model?
  – How do the result depend on the data?
  – Is the model well-suited for numerical treatment?

• Seldom a single model – model hierarchy:
  – Different length and time scales
  – Accuracy versus complexity

Why mathematical models?

Mathematics and mathematical models can be used to model all objects and processes.

Using models we can:
• Idealize processes and phenomena
• Control contributions from the environment
• Explore when experiments are difficult or impossible
• Explore more cost-efficient
• Explore without potential safety issues
But how is this done?

Model

Experiment

Simulation

Modern development of models for a physical phenomenon

Start: around 1945

John von Neumann:

“Indeed, to a great extent, experiments in fluid mechanics are carried out under conditions where the underlying physical principles are not in doubt, where the quantities to be observed are completely determined by known equations. The purpose of the experiment is not to verify a proposed theory but to replace a computation from an unquestioned theory by direct measurements.”

Elected “Man of the Century” by Financial Times and (step)father of ENIAC (Electronic Numerical Integrator and Computer)

So, what is simulation?

Simulation denotes the process of exploring mathematical models of phenomena and processes by the means of a computer.

Ingredients:
- Phenomena and processes (natural, man-made, virtual, ...)
- Insight (physics, chemistry, biology, economics, ...)
- Mathematical models (often expressed by PDEs)
- Numerical methods (i.e., computer algorithms)
- Software implementation
- Computer experiments
- Extraction and interpretation of results (i.e., numbers)

Challenges in simulation

- Multiscale phenomena (e.g., reservoir simulation)
- Multiphysics (fluid-structure interaction)
- Complicated and time-dependent geometries
- Time-dependence (unsteady and transitional phenomena)
- Varying accuracy requirements (adaptivity)
- Lack of data and parameters
- Higher dimensions (quantum mechanics, finance, ...)
- Poor performance of standard methods (when applied to nonstandard problems)
- Hardware requirements (memory, processing speed, ...)
- Software requirements
- ...*

What is visualization?

Visualization: the act or process of interpreting in visual terms or of putting into visual form.

In other words: to increase the human understanding of something by the means of images, series of images or other visual manifestations.

For scientific visualization this “something” means data sets in some form, most usually large sets of numbers resulting from an experiment or a computation.

The Simulation Pipeline

Mathematical Model

Processes

Computations

Results

Retirement

Prediction & Control

Decision & Control
**Widely used today**

Simulation and visualization find applications in:
- “All” engineering disciplines
- Physics (astro, geo, nuclear, …)
- Biology and medicine
- Ecosystems and environment
- Meteorology, oceanography
- Entertainment industry (movies, TV, games,...)
- Financial and assurance market
- …

Simulation is always stretching the limits of what is Computationally and mathematically feasible…

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**New Understanding of Life Processes**

Simulation is important in the exploration of life processes, ranging from studies of DNA to investigations of blood circulation and inner organs like the heart, brain and lungs.

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**Heartbeats and Flowing Blood**

Millions of people suffer from atherosclerosis. Fatty blockages of the arteries gradually obstruct blood flow and ultimately causes the heart to stop beating. This remains one of the leading causes of heart attacks around the world.

Simulation of blood and other complex fluid flows may lead to changes in accepted surgical practices that will dramatically extend the life expectancy of those suffering from arterial diseases like atherosclerosis.

Attempts are made to develop arterial grafting techniques that will reduce atherosclerosis build up. Various graft designs can be tested through accurate simulations of the blood flow. In a few years computations may be used by surgeons on a routine basis to evaluate graft designs and chose the one that is best suited for the individual patient.

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**Electrical Heart Activity**

Simulation of the electrical activity in the human heart based on a model coupling several PDEs and ODEs.

The visualized electrical potential represents a period of 250 ms. This problem is extremely demanding in terms of computational resources and requires advanced solution methods and fast hardware.

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**Manufacturing Processes**

Today, almost any industrial branch use simulation as a tool for evaluating, predicting and optimizing the manufacturing processes. This is mainly due to better cost effectiveness and reduced risks.
Aerospace and Automotive Industries

Car crash simulations

Oil exploration and Gardermobanen

Oil flowing into a well in the North Sea
Water flowing into Romeriksposten

Exactly the same mathematics (equations) and exactly the same simulation software (TSC inc, 1997)

Computing how such waves arise near offshore installations requires very advanced mathematics and accurate computations

- and is of vital interest for offshore security in the North Sea

Wave height measured under the deck of the Draupner-platform (Statoil) January 1, 1995. The platform deck is lower than 18 meters.

Software - The Heart of Simulation

- Over the last 50-55 years
  - Computers have become more than 1,000,000 times faster.
  - Numerical methods for typical PDEs have become more than 1,000,000 times faster
  - The number of applications has exploded
- Software quality has become a major bottleneck.
- This awareness has lead to the influx of modern software principles into scientific computing.
- Today: object-oriented software is becoming increasingly more important.
At any time scientists want to fill the largest and fastest computers to solve their problems:
- by adding complexity
- by using finer grid resolutions (more data) in order to get better results

Split problem into sub-problems, solve in parallel on many CPUs (or computers).

Beyond the Teraflop

June 1997: Full ASCI Red at Sandia National Lab achieves 1.3 teraflops (teraflop = trillion floating point operations).

Today: check out http://www.top500.org

It is a real challenge!

Simulation has increasing influence:
- More product designs are based on simulation
- More decisions are based on simulation

This means that simulations:
- should be reliable
- should be efficient
- aim at solving problems of very high complexity, and the complexity is always increasing
- are often performed in cases there is no or very little theory available
- is interdisciplinary in nature and involve a wide knowledge base (physics, mathematics, numerics, computer science...)

So, you should really know what you are doing!

The Sleipner platform

Sleipner A platform:
- Condeep platform
- 82 m water depth
- 24 cells with total base area 16 000 m²
- Top deck 57 000 tons
- Drilling equipment weighing 40 000 tons
- Accommodation for 200 people

The Sleipner A incident

23 August 1991: Concrete base structure sprang a leak and sank in Gandalf tender outside Stavanger:
- The crash caused a seismic event registered 3.0 on the Richter scale
- All that was left was a pile of debris at 220 m of depth
- Total economic loss of about $700 million.

Cause of accident:
- Failure in cell wall, leading to uncontrolled leakage
- Inaccurate FEM (in NASTRAN) -> shear stresses underestimated by 47% -> too thin concrete walls in supporting cells

Refined analysis:
- Failure at 62 m of depth as opposed to actual occurrence at 65 m

What about this course?

You will learn five things:
- a taste of modeling and simulation
  - very simple problems, still with relevance to the real world
- a taste of numerical methods
  - finite differences, ODEs, PDEs
- visualization and some basic computer graphics
- programming in C++
  - and special issues for applications in scientific computing
- VTK

We cover some theory, but the emphasis is on the practical applications (i.e., kind of a laboratory course)
- A two-level approach

In the simulation part:
- We learn about basic methods and concepts
- We implement codes/libraries from scratch

In the visualisation part:
- We learn about basic and advanced methods
- We build upon pre-existing software libraries

Altogether, this gives a view of the real world you might meet in scientific computing