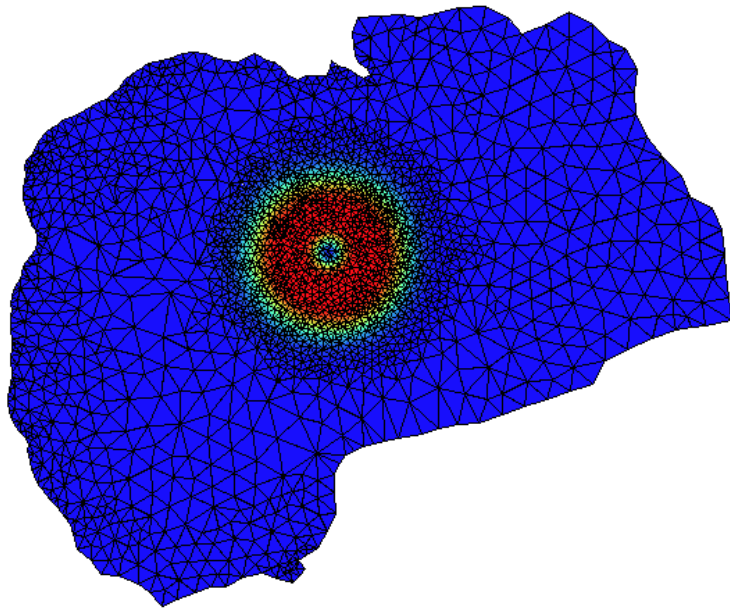


Reduced-gravity simulation of a baroclinic eddy in the Gulf of Mexico.

This simulation is several orders of magnitude cheaper than a constant resolution one of the same accuracy !

The Finite Element Method



Typical applications

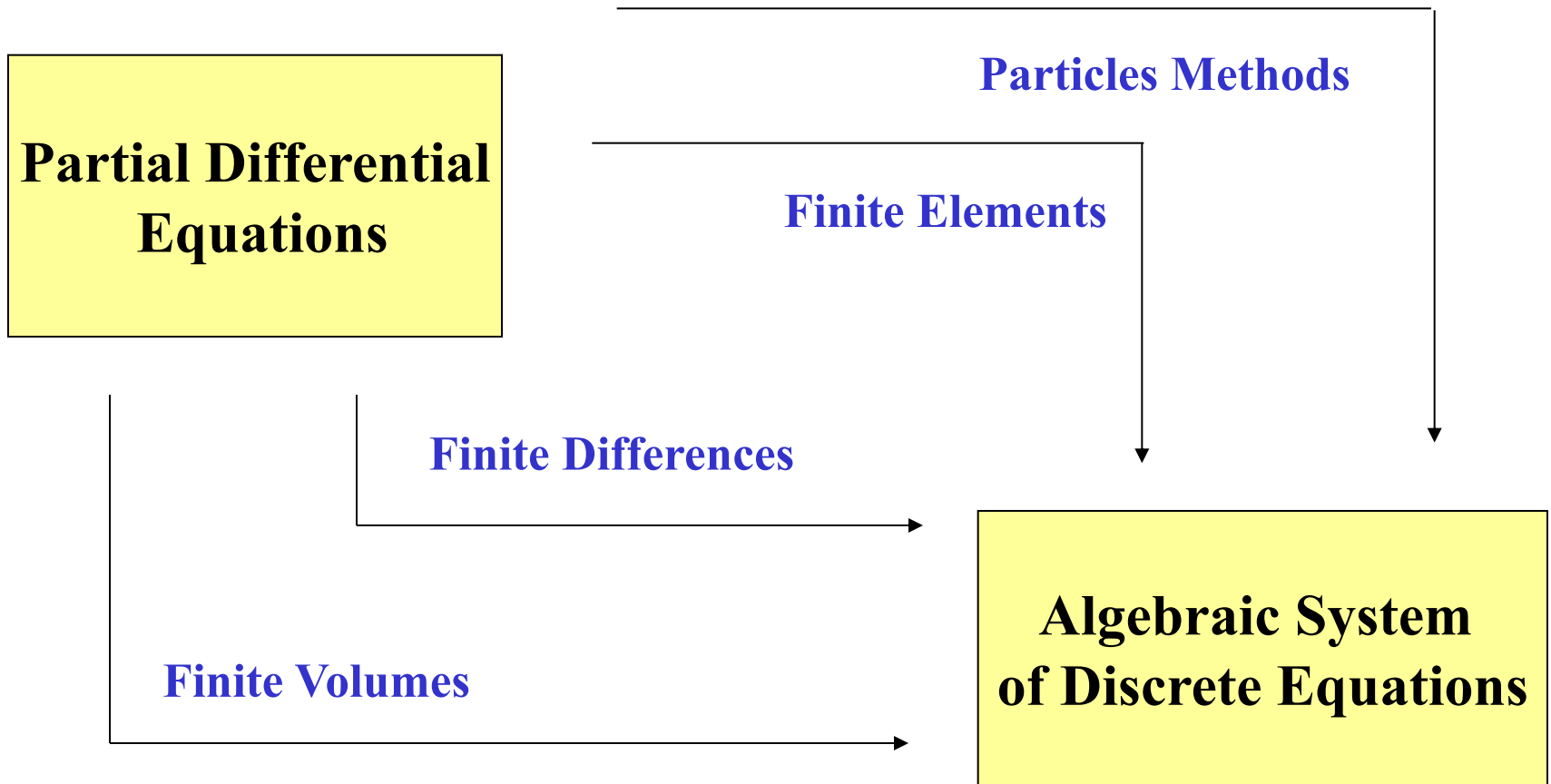
Deformable solids mechanics
Fluid dynamics (CFD)
Electromagnetism
Transport phenomena
Climatology

is a way of computing approximate solutions to a mathematical model describing a physical process.

What is a mathematical model ?
A boundary value problem.

What is a boundary value problem ?
A set of partial differential equations with boundary and initial conditions.

Finite Elements, Finite Differences, Finite Volumes etc.

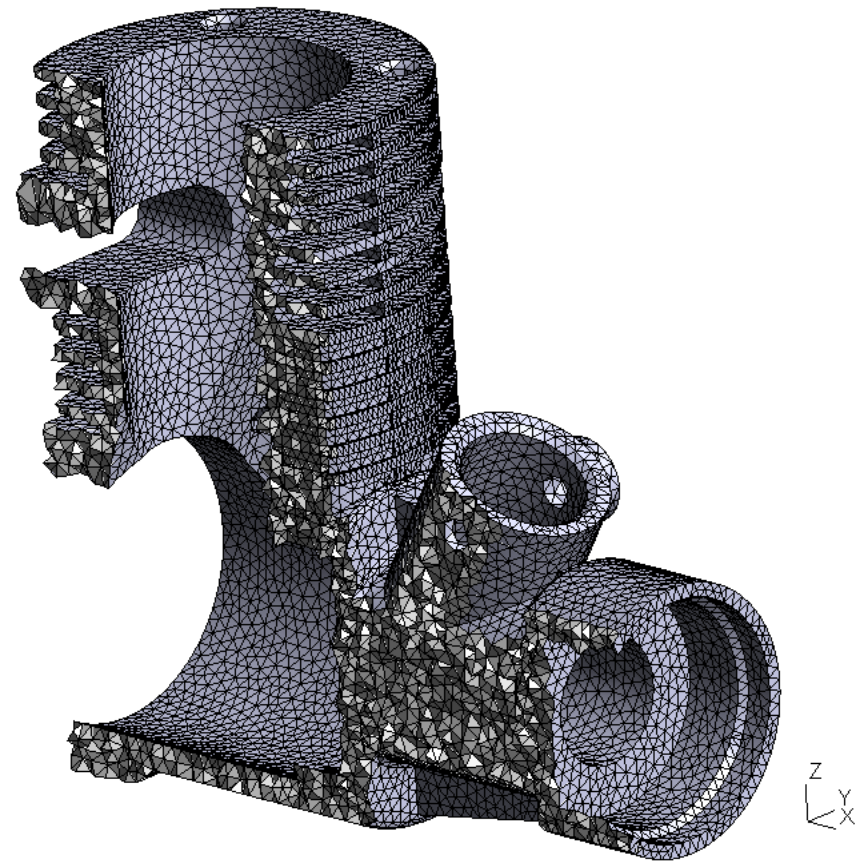


The Finite Elements Method is a discretization method

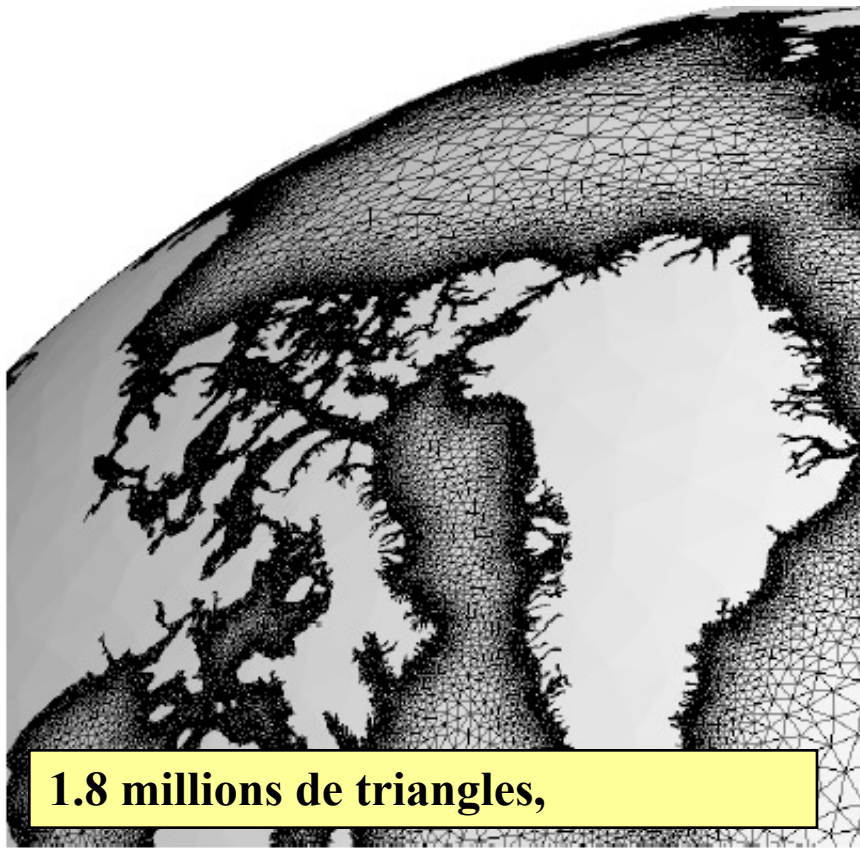
The problem geometry is divided in
small finite elements.

On each element, the solution is
approximated by means of unknown
nodal values and given polynomials

$$u(\mathbf{x}) \approx u^h(\mathbf{x}) = \sum_{j=1}^n U_j \tau_j(\mathbf{x})$$



Second-generation Louvain-la-Neuve Ice-ocean Model



Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities

http://geuz.org/gmsh/

Page précédente Page suivante Actualiser

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Méthodes numériq... Apple Finite Elements Cazou Informations Papers UCL Web servers À la une Nouvelobs.com en... OpenGL MECA2300 MECA2170

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Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities

Christophe Geuzaine and Jean-François Remacle

Version 2.3.1, March 18 2009

[Description](#) | [Download](#) | [Authors and credits](#) | [Documentation](#) | [Mailing lists](#) | [Licensing](#) | [Screenshots](#) | [Links](#)

Description

Gmsh is an automatic 3D finite element grid generator with a built-in CAD engine and post-processor. Its design goal is to provide a simple meshing tool for academic problems with parametric input and advanced visualization capabilities.

Gmsh is built around four modules: geometry, mesh, solver and post-processing. The specification of any input to these modules is done either interactively using the graphical user interface or in ASCII text files using Gmsh's own scripting language.

See the screencasts for a [quick tour of Gmsh's graphical user interface](#), or the reference manual for a more thorough [overview of Gmsh's capabilities](#).

Download

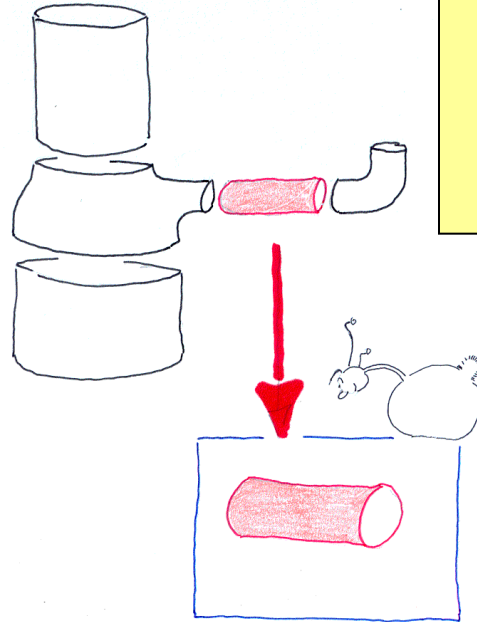
Gmsh is distributed under the terms of the [GNU General Public License \(GPL\)](#). Pre-compiled binaries are available for Windows (XP & Vista), Linux (Intel, glibc 2.3) and Mac OS X (10.5, Universal binary). Tutorial and demos files are included in all the archives.

- Current stable release: [Windows](#), [Linux](#), [Mac OS X](#) and [source code](#) ²
- Experimental versions (these might be buggy, or might not even launch: use at your own risk!):
 - automated nightly builds: [Windows \(build log\)](#), [Linux \(build log\)](#), [Mac OS X \(build log\)](#)
 - nightly [cvs source snapshots](#)
- [Remove all references, histories, and sources](#)

Terminé

1.8 millions de triangles,

Classical Engineering Analysis



**Exact solution
to approximate problems**

**Analysis through simple geometries
and a limited combination of
approximate models :**

**Lubrication theory
Bars
Beams
Plates and shells**

**Low computer's cost
Good physical understanding**

Simplicity of models

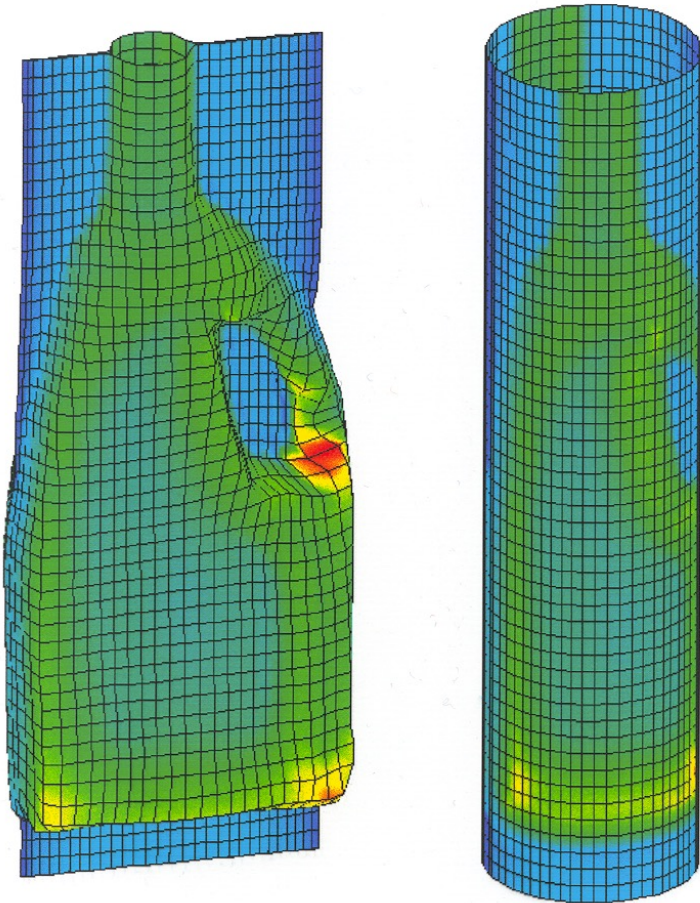
Complex geometries and loads cannot be handled

Complex materials cannot be analyzed

Computer Aided Engineering Analysis

The Finite Element Method provides approximate solutions to more realistic problems

FEM developed in the sixties for linear elasticity and generalized to many other applications...



Powerful and flexible

High (cheap) computer's cost

Low (expensive) engineer's cost

Complex processes can be analyzed

Complex material laws can be included

However...

Garbage in



Garbage out

Illusion of non-qualified users to be able to analyze everything

New modeling issues requires higher qualifications...

How to define complex problems in an accurate and efficient way for the computer software ?

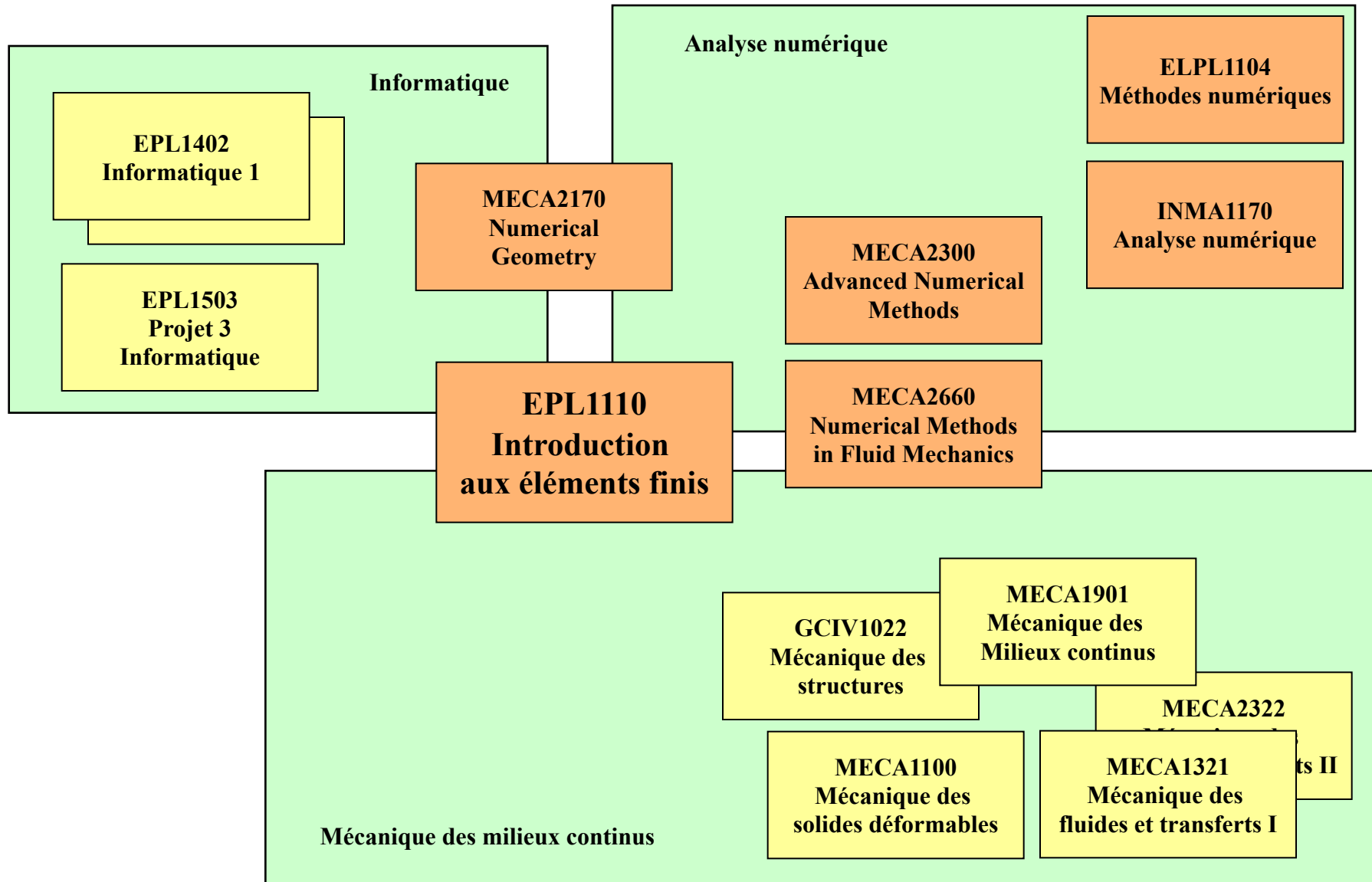
A l'issue de ce cours, vous serez capables de...

- **Comprendre la méthode des éléments finis**
- **Réaliser un petit programme en C**
- **Certifier et valider une simulation**
- **Choisir la voie numérique la plus efficace**
- **Estimer la précision d'un résultat**
- **Découvrir les joies et les aléas du numérique**

Non, non : ceci on ne fera pas !

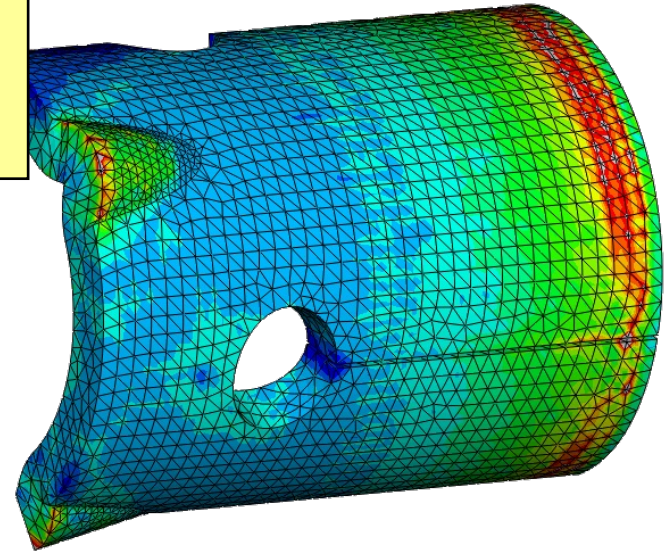
- **Apprendre le génie logiciel de l'orienté-objet**
- **Utiliser des logiciels commerciaux**
- **Faire de l'analyse numérique théorique**
- **Faire du calcul parallèle**
- **Résoudre les équations de Navier-Stokes**
- **Créer automatiquement des maillages**

Et les autres cours....



Plan du cours et évaluation

Comment intégrer
numériquement
une fonction
sur un carré ?



Comment résoudre
l'élasticité linéaire ?

Evaluation continue

S1-S8 : 8 cours et 8 petits problèmes **A**

Evaluation certificative

S2-S10 : séances d'exercices

S10-S13 : mini-projet **B**

S9 : interrogation **C**

En juin, note finale = $(A+B+C)/3$ **si** $(B+C) > 10$
= $(B+C)/2$ **sinon**

En septembre, examen oral + projet spécial

Evaluation

Objectifs du projet

Réaliser	Créer une application pour prédire un tsunami.
Certifier	Tester et valider le travail de votre groupe.
Expliquer	Expliquer de manière efficace et rapide à l'enseignant et aux autres étudiants ce que vous avez réalisé.
Comprendre	Comprendre ce que vous avez réalisé. Comprendre ce que d'autres groupes ont réalisé.

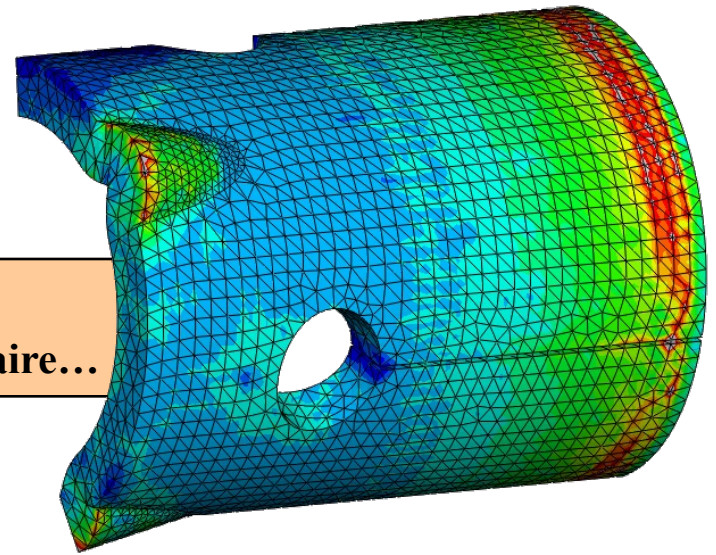
Exercices : 8 petits problèmes

Quelques petits problèmes
élémentaires pour apprivoiser le C

Projet en C :

Une petite application efficace pour l'élasticité linéaire...

The Practice of Programming :
Simplicity, Clarity, Generality. (B.K Kernighan & R. Pike 99)



Elasticité linéaire pourquoi ?

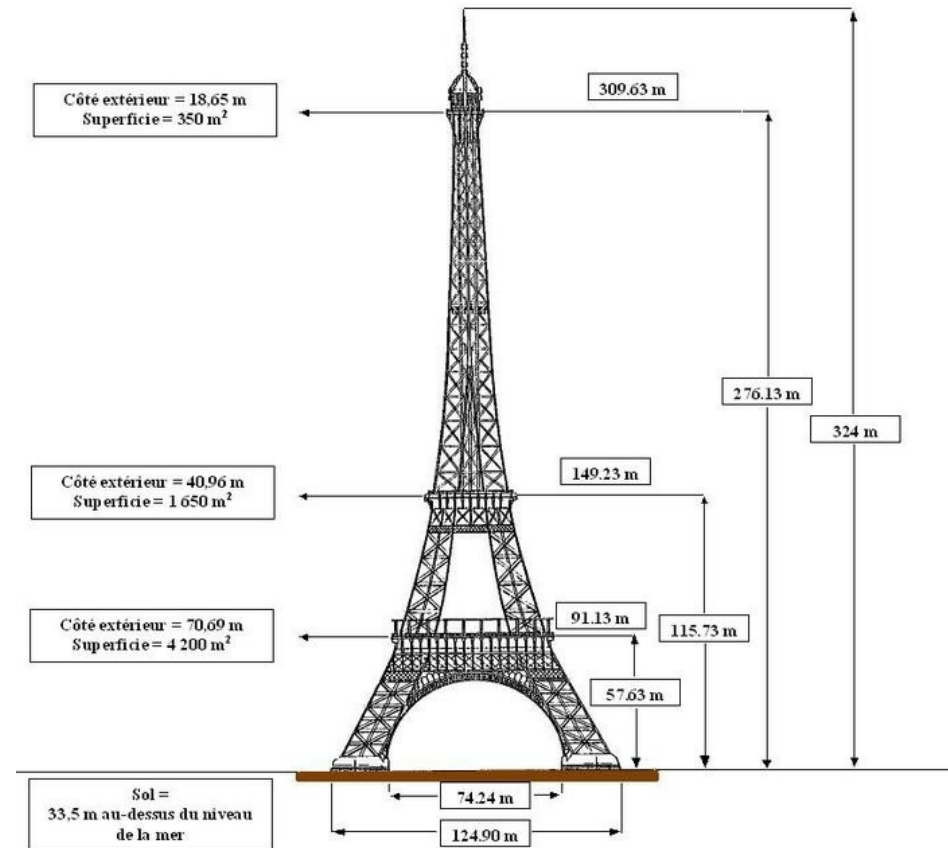
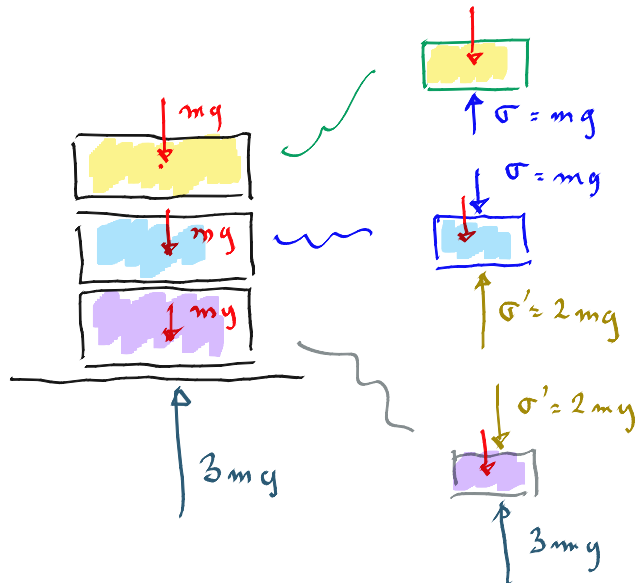
Centrale nucléaire de Tihange 1

Rapport de synthèse
Long Term Operation 2015-2025
Version finale



(Suite en dernière page)

Monsieur,
j'ai pas eu MMC, moi ?

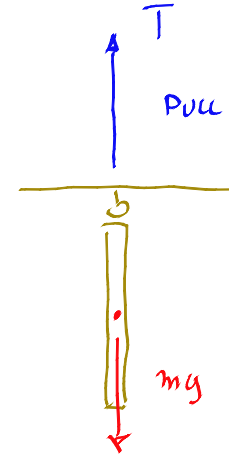
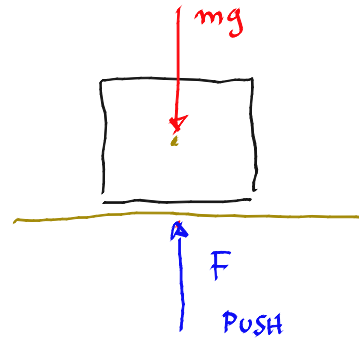


Ouuupps !

Mais, MMC, MSD et Flotte : quelle horreur !

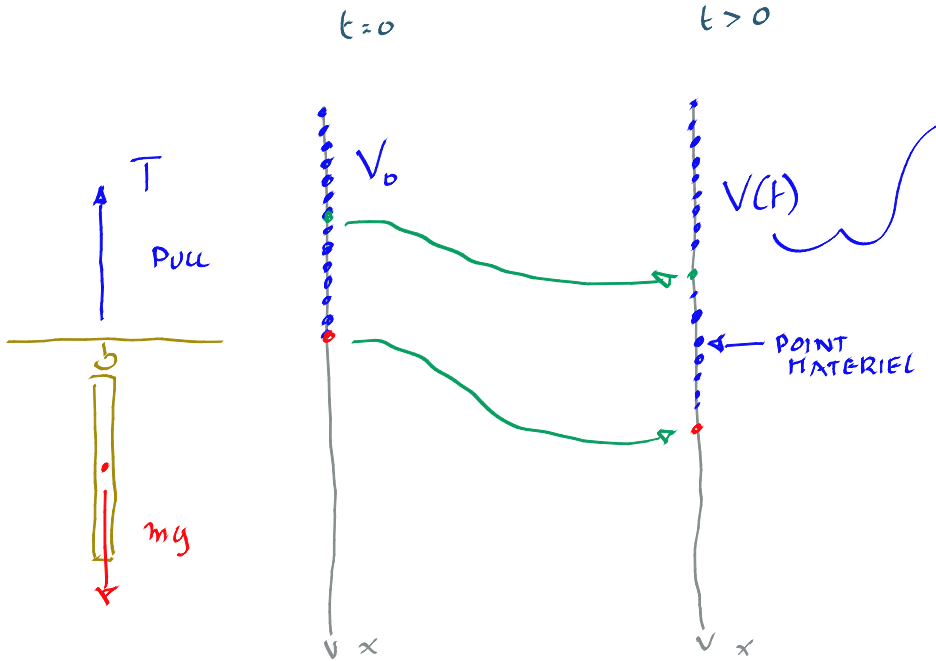
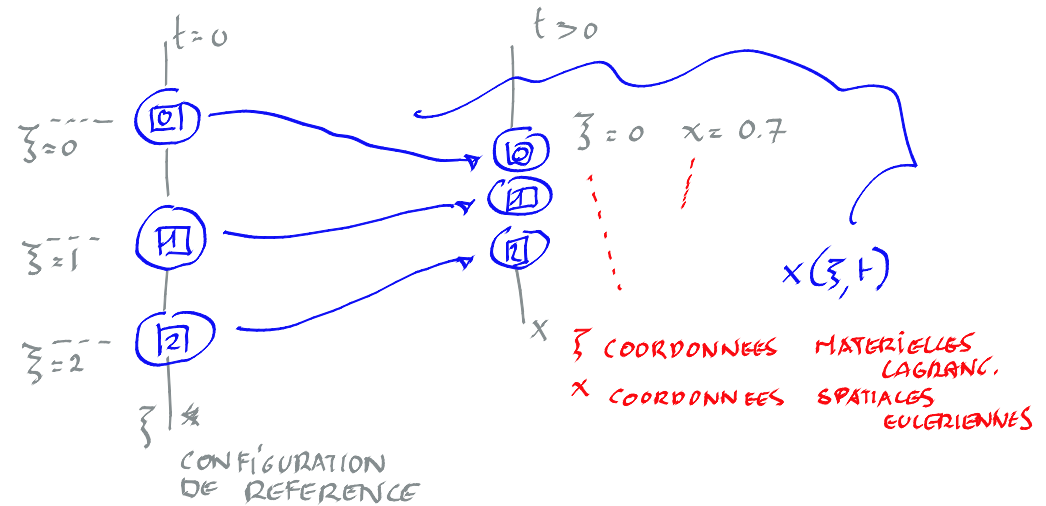
Souviens-toi des anciens !
Le grand Newton !
L'inoubliable Roland !

$$m \frac{d^2x}{dt^2} = \sum \vec{F}$$



Un volume matériel !

$$\mathcal{V}(x, t)$$



VOLUME MATERIEL

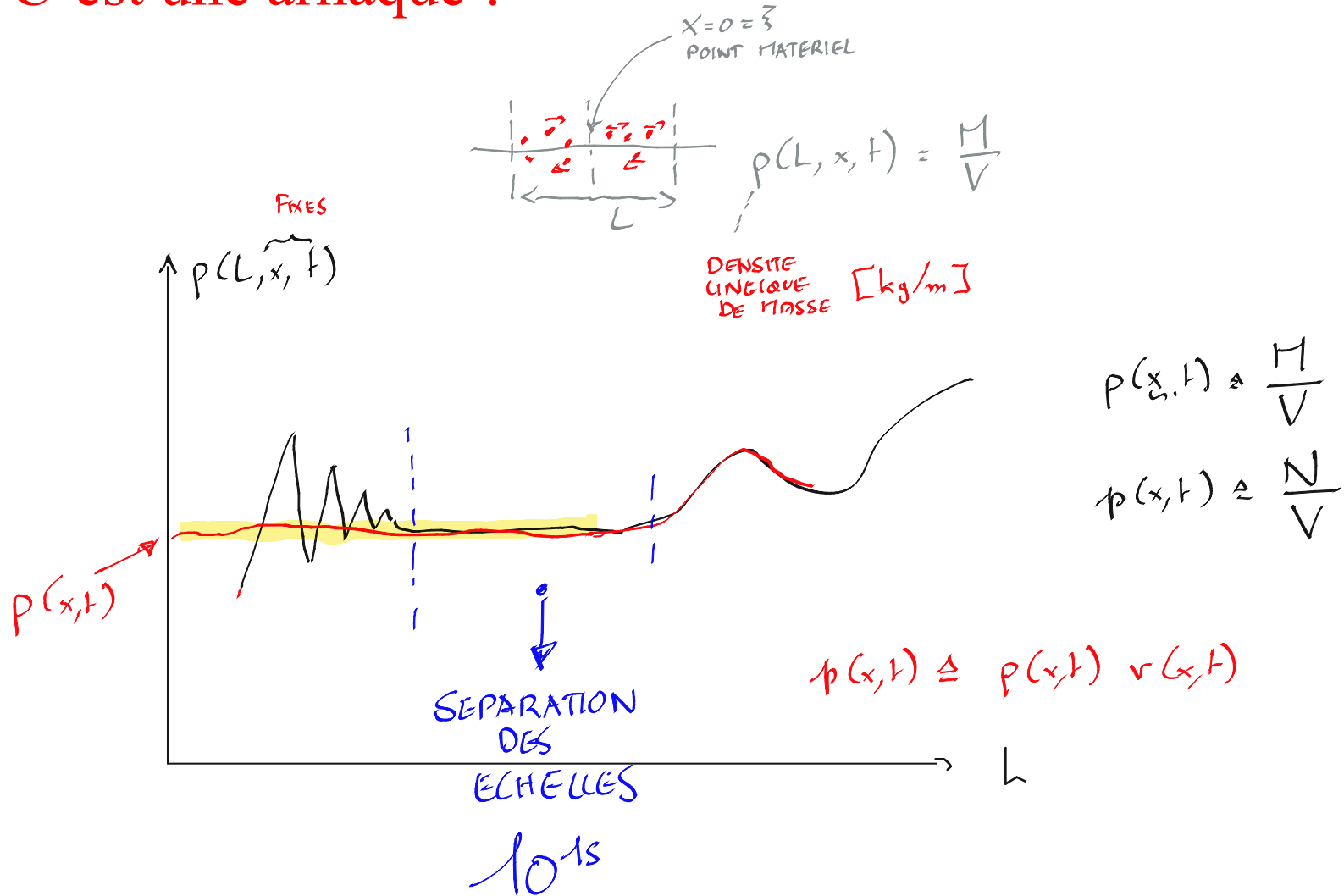
= ENSEMBLE DE POINTS MATERIELS SE DEPLACANT A UNE VITESSE

$$\mathcal{V}(x, t) = \int v_i(x, t) \hat{e}_i$$

VITESSE MACROSCOPIQUE !

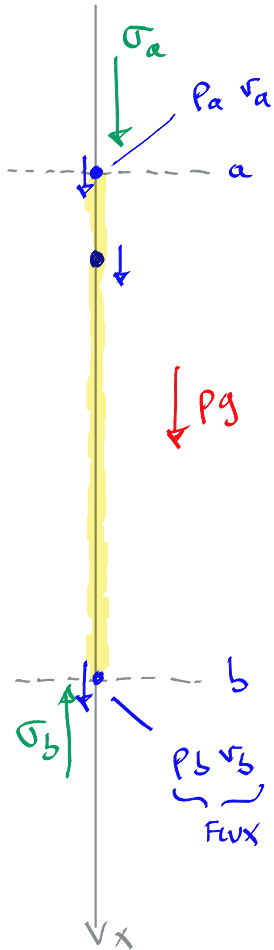
La mécanique des milieux continus !

C'est une arnaque !



Bilan de quantité de mouvement

$\sigma < 0$ COMPRESSION
 $\sigma > 0$ TRACTION



Δx INTERVALLE

L'ACCROISSEMENT
DE QUANTITE
DE MVT

$$= \text{CE QUI ENTRE} - \text{CE QUI SORT} + \text{FORCES}$$

$[\sigma]_a^b$

$$\frac{d}{dt} \int_a^b \rho(x,t) v(x,t) dx = \underbrace{p_a v_a^2 - p_b v_b^2}_{- [\rho v^2]_a^b} + \int_a^b \rho g + \underbrace{(-\sigma_a) - (-\sigma_b)}_{\sigma_b - \sigma_a}$$

FORME GLOBALE

$$\int_a^b \frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial x} (\rho v^2) dx = \int_a^b \rho g + \frac{\partial \sigma}{\partial x}$$

$$\underbrace{\frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial x} (\rho v^2)}_{\rho \frac{Dv}{Dt}} = \rho g + \frac{\partial \sigma}{\partial x}$$

FORME LOCALE

hello.c

```
#include <stdio.h>

int main()
{
    printf("hello, world\n");
    return 0;
}
```

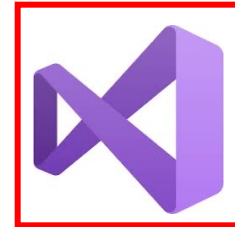
*Vous aimeriez apprendre à programmer,
mais vous ne savez pas par où commencer ?*

*(autrement dit : vous en avez marre des cours trop
compliqués que vous ne comprenez pas ? :-)*



```
Cours1 -- bash -- 71x16
Last login: Fri Feb 4 08:32:27 on ttys001
(base) mac-100-352:~ vl$ cd LaTeX/ep11110-2122/Slides/Cours1
(base) mac-100-352:Cours1 vl$ ls
a.out  hello.c
(base) mac-100-352:Cours1 vl$ touch hello.c
(base) mac-100-352:Cours1 vl$ cc hello.c
(base) mac-100-352:Cours1 vl$ ./a.out
hello, world
(base) mac-100-352:Cours1 vl$
```

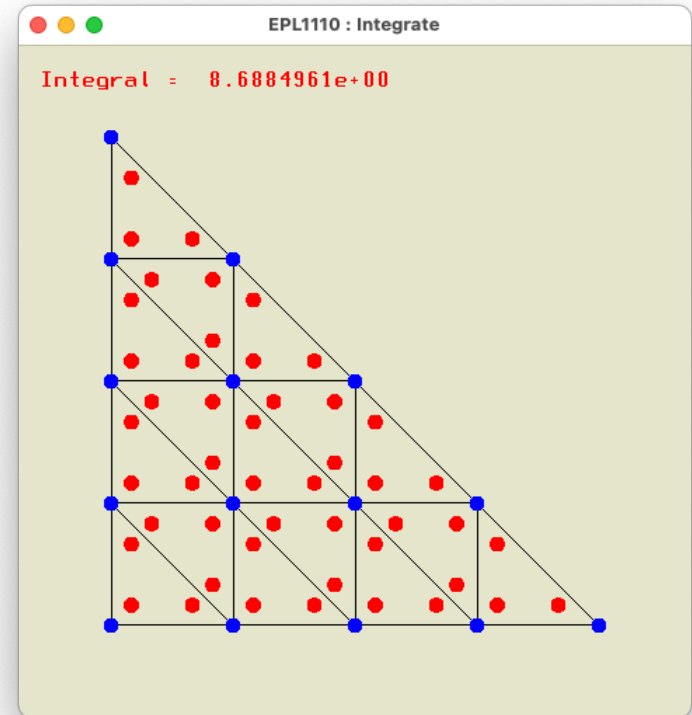
Comment compiler hello.c sur votre ordinateur ?



```
Cours1 -- -bash -- 93x27
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
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(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$
(base) mac-100-352:Cours1 vl$ touch hello.c
(base) mac-100-352:Cours1 vl$ cc -c hello.c
(base) mac-100-352:Cours1 vl$ ls
hello.c hello.o
(base) mac-100-352:Cours1 vl$ cc -o hello hello.c
(base) mac-100-352:Cours1 vl$ ./hello
hello, world
(base) mac-100-352:Cours1 vl$ cc -o yep hello.o
(base) mac-100-352:Cours1 vl$ ./yep
hello, world
(base) mac-100-352:Cours1 vl$
```

Homework 1

$$\underbrace{\int_{\hat{\Omega}} f(x, y) \, dx \, dy}_I \approx \underbrace{\sum_{k=1}^3 w_k f(x_k, y_k)}_{I_h}$$



Ecrire la règle de Hammer

mainBasic.c

```
#include <stdio.h>
#include <math.h>

double integrate(double x[3], double y[3], double(*f)(double,double));
double integrateRecursive(double x[3], double y[3], double(*f)(double,double), int n);

double fun(double x, double y) { return cos(x) + y * y; }
double stupid(double x, double y) { return 1.0; }

int main()
{
    double x[3] = {0, 1, 0};
    double y[3] = {0, 0, 1};
    int n;
    printf("Surface integration      : %14.7e \n", integrate(x,y,stupid));
    printf("More funny integration : %14.7e \n", integrate(x,y,fun));
    for (n=0; n <= 4; n++) {
        double I = integrateRecursive(x,y,fun,n);
        printf("Recursive integration (n = %2d) : %14.7e \n", n,I);
    }
    return 0;
}
```

homework.c et mainBasic.c

```
double integrate(double x[3], double y[3], double (*f) (double, double))
{
    double I = 3.14;
    return I;
}
```

```
double integrateRecursive(double x[3], double y[3], double (*f)(double,double), int n)
{
    double I = 0.0;
    return I;
}
```

```
double fun(double x, double y) { return cos(x) + y * y; }
double stupid(double x, double y) { return 1.0; }
```

```
int main()
{
    double x[3] = {0, 1, 0};
    double y[3] = {0, 0, 1};
    int n;
    printf("Surface integration      : %14.7e \n", integrate(x,y,stupid));
    printf("More funny integration : %14.7e \n", integrate(x,y,fun));
    for (n=0; n <= 1; n++) {
        double I = integrateRecursive(x,y,fun,n);
        printf("Recursive integration (n = %2d) : %14.7e \n", n,I); }
    return 0;
}
```

Comment compiler le devoir sur votre ordinateur ?



homework.c



homeworkSoluce.c



mainBasic.c

```
Cours1 — -bash — 79x29
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$
(base) mac-1U0-352:Cours1 v1$ cc -o myFem mainBasic.c homework.c
(base) mac-1U0-352:Cours1 v1$ ./myFem
Surface integration      : 3.1400000e+00
More funny integration  : 3.1400000e+00
Recursive integration (n = 0) : 0.0000000e+00
Recursive integration (n = 1) : 0.0000000e+00
Recursive integration (n = 2) : 0.0000000e+00
Recursive integration (n = 3) : 0.0000000e+00
Recursive integration (n = 4) : 0.0000000e+00
(base) mac-1U0-352:Cours1 v1$ cc -o myFem mainBasic.c homeworkSoluce.c
(base) mac-1U0-352:Cours1 v1$ ./myFem
Surface integration      : 5.0000000e-01
More funny integration  : 5.4302895e-01
Recursive integration (n = 0) : 5.4302895e-01
Recursive integration (n = 1) : 2.1721229e+00
Recursive integration (n = 2) : 8.6884961e+00
Recursive integration (n = 3) : 3.4753986e+01
Recursive integration (n = 4) : 1.3901594e+02
(base) mac-1U0-352:Cours1 v1$
```


Bon : c'est aussi simple ?

perso.uclouvain.be/vincent.l

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Introduction aux éléments finis (LEPL1110)
Vincent Legat
Jean-François Remacle
Louvain School of Engineering
Université catholique de Louvain

Il faut d'abord t'identifier :-)

News Documents Videos & podcasts !

Comment obtenir un exécutable sur votre ordinateur ? Programmes Python Devoirs en C

Devoirs en C...
Les énoncés seront disponibles progressivement...

Devoir 1 : Integrate (02-02-2022)
Projet à télécharger : Integrate.zip
Enoncé du devoir : Integrate.pdf
Deadline : **Lundi 14 février 2022 à 23h59**

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```
src -- -bash -- 90x27
IntegrateWithoutBov  homework.c      myFem
hello                homeworkSoluce.c  yep
hello.c              mainBasic.c

(base) mac-1U0-352:Cours1 v1$ cd Integrate
(base) mac-1U0-352:Integrate v1$ ls
CMakeLists.txt  glfw      src
(base) mac-1U0-352:Integrate v1$ cd src
(base) mac-1U0-352:src v1$ ls
fem.c           glfem.c      homework.c
fem.h           glfem.h      main.c
(base) mac-1U0-352:src v1$ gcc -o myFem *.c
In file included from glfem.c:10:
./glfem.h:21:10: fatal error: 'GLFW/glfw3.h' file not found
#include <GLFW/glfw3.h>
          ^~~~~~
1 error generated.
In file included from homework.c:3:
./glfem.h:21:10: fatal error: 'GLFW/glfw3.h' file not found
#include <GLFW/glfw3.h>
          ^~~~~~
1 error generated.
In file included from main.c:5:
./glfem.h:21:10: fatal error: 'GLFW/glfw3.h' file not found
#include <GLFW/glfw3.h>
          ^~~~~~
1 error generated.
(base) mac-1U0-352:src v1$
```

Eh non !

perso.uclouvain.be/vincent.legat/zouLab/ep1110.php?action=

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Exécution et soumission d'un programme sur le serveur...

Groupe : 1 (viegat-jeremacle)
Binôme : Remacle, Jean-François
Deadline : February 14 2022 23:59:59.
Now : February 04 2022 09:04:25.

```
1 #include <math.h>
2
3
4 #include "gifem.h"
5
6
7
8
9
10
11
```

Position: Ln 11, Ch 1 Total: Ln 65, Ch 1656

Exécuter le programme sur le serveur Voir le diagnostic

Valider son programme


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perso.uclouvain.be/vincent.legat/zouLab/ep1110.php?...

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Introduction aux éléments finis (LEPL110)

Vincent Legat
Jean-François Remacle
Louvain School of Engineering
Université catholique de Louvain

News Documents Videos & podcasts !

Comment obtenir un exécutable sur votre ordinateur ? Programmes Python Devoirs en C

Liste des étudiants Liste des groupes Equipe didactique Former son groupe

Soumettre le devoir 1 Integrate

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Soumettre votre devoir !

**Tous les devoirs seront corrigés de manière automatique !
Bien veiller à ce que la version soumise soit bien compilée !
Aucune soumission tardive ne sera admise !
Les devoirs sont réalisés individuellement !**

perso.uclouvain.be/vincent.legat/zouLab/epi

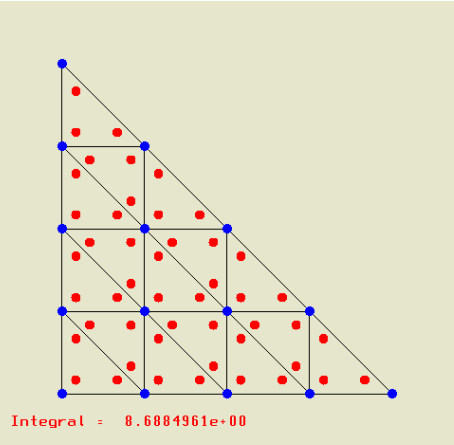
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Exécution et soumission d'un programme sur le serveur...

Groupe : 1 (vlegat-jeremacle)
Binôme : Remacle, Jean-François
Deadline : February 14 2022 23:59:59.
Now : February 04 2022 09:06:11.



Integral = 8.6884961e+00

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```
int i,j;
const int nodes[4][3] = {{0,3,5},{3,1,4},{5,4,2},{3,4,5}};
const double xsi[6] = {0.0,1.0,0.0,0.5,0.5,0.0};
const double eta[6] = {0.0,0.0,1.0,0.0,0.5,0.5};
double xLoc[3];
double yLoc[3];

if (n <= 0) return integrate(x,y,f);

double I = 0.0;
for (i=0; i<4; i++) {
  for (j=0; j<3; j++) {
    double xsiLoc = xsi[nodes[i][j]];
    double etaLoc = eta[nodes[i][j]];
    xLoc[j] = interpolate(x,xsiLoc,etaLoc);
    yLoc[j] = interpolate(y,xsiLoc,etaLoc); }
  I += integrateRecursive(xLoc,yLoc,f,n-1); }

return I;
}
```

👍 👍 👍 👍 👍 ❤️ ❤️ ❤️ ❤️

Faire une nouvelle soumission Voir le diagnostic

Valider son programme

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Valider
et verifier son devoir !

homework.c

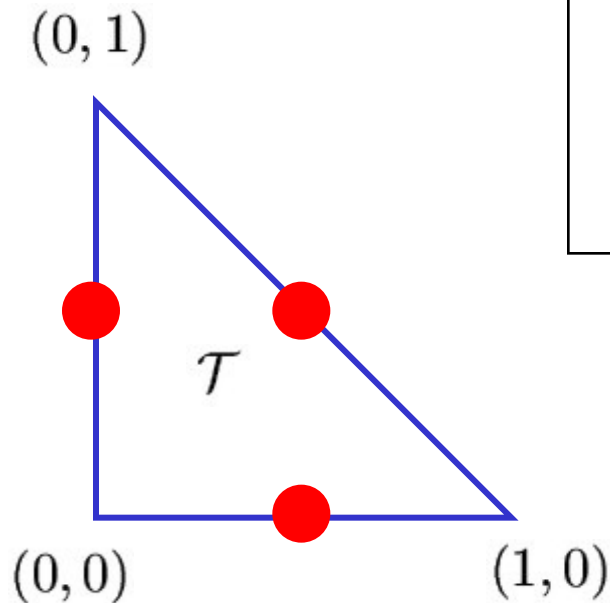
La solution doit se trouver dans le fichier homework.c
uniquement.... On ne regarde jamais main.c !

```
#include <stdio.h>
#include <math.h>

double integrate(double x[3], double y[3], double (*f) (double, double))
{
    double I = 3.14;
    int I;
    for (i=0; i<3; i++)
        printf("    == node %d : %14.7e %14.7e \n",i+1,x[i],y[i]);
    return I;
}

double integrateRecursive(double x[3], double y[3], double (*f) (double,double), int n)
{
    double I = 0.0;
    return I;
}
```

Intégration sur un triangle : Règle de Hammer à 3 points



$$\underbrace{\int_{\mathcal{T}} f(x,y) \, dx \, dy}_I \approx \underbrace{\sum_{k=1}^3 w_k f(X_k, Y_k)}_{I^h}$$

	X_k	Y_k	w_k
1	0.5	0.0	1/6
2	0.5	0.5	1/6
3	0.0	0.5	1/6

Démontrer que la formule de Hammer à trois points permet d'intégrer exactement n'importe quel polynôme à deux variables de degré deux : $a + bx + cy + dx^2 + ey^2 + fxy$

Question

$$\begin{aligned}
 I &= \frac{a}{2} + b \int_0^1 x \int_0^{1-x} dy \, dx + c \int_0^1 y \int_0^{1-y} dx \, dy \\
 &\quad + d \int_0^1 x^2 \int_0^{1-x} dy \, dx + e \int_0^1 y^2 \int_0^{1-y} dx \, dy + f \int_0^1 x \int_0^{1-x} y \, dy \, dx \\
 &= \frac{a}{2} + b \left[\frac{x^2}{2} - \frac{x^3}{3} \right]_0^1 + c \left[\frac{y^2}{2} - \frac{y^3}{3} \right]_0^1 \\
 &\quad + d \left[\frac{x^3}{3} - \frac{x^4}{4} \right]_0^1 + e \left[\frac{y^3}{3} - \frac{y^4}{4} \right]_0^1 + f \left[\frac{x^2}{4} - \frac{x^3}{3} + \frac{x^4}{8} \right]_0^1 \\
 &= \frac{a}{2} + \frac{b}{6} + \frac{c}{6} + \frac{d}{12} + \frac{e}{12} + \frac{f}{24} \\
 &= I^h
 \end{aligned}$$



Degré de
précision

Et un autre triangle ?

$$\begin{aligned}x' &= 10x \\y' &= 15 - 15y\end{aligned}$$

