Verrou:

A Tool to Reproduce Floating-Point-Induced Non-Reproducibilities

(and help fix them)

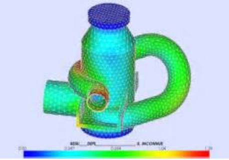
MDS workshop
June 28th, 2019

François Févotte*
Bruno Lathuilière

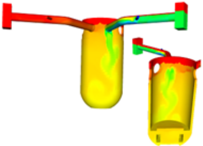
EDF R&D
Analysis and Numerical Modeling

Industrial context – Numerical Verification

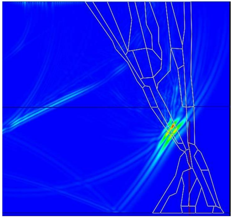
In-house development of Scientific Computing Codes



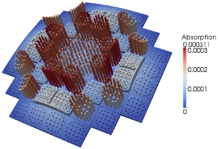
Structures



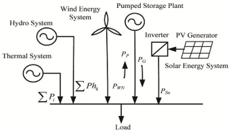
Fluid dynamics



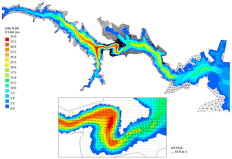
Wave propagation



Neutronics



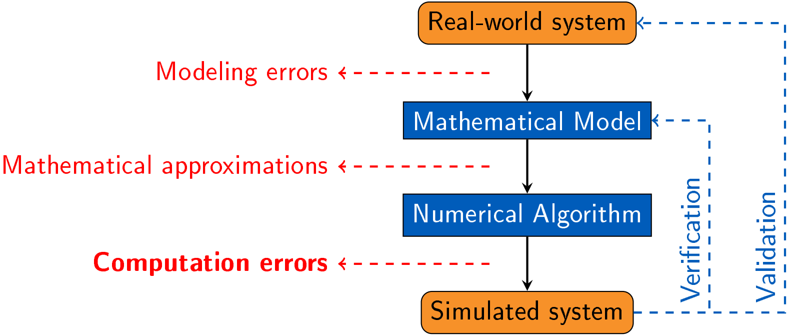
Power Systems



Free surface hydraulics

Industrial context – Numerical Verification

Verification & Validation



Real-world system

Modeling errors

Mathematical Model

Mathematical approximations

Numerical Algorithm

Computation errors

Simulated system

Verification

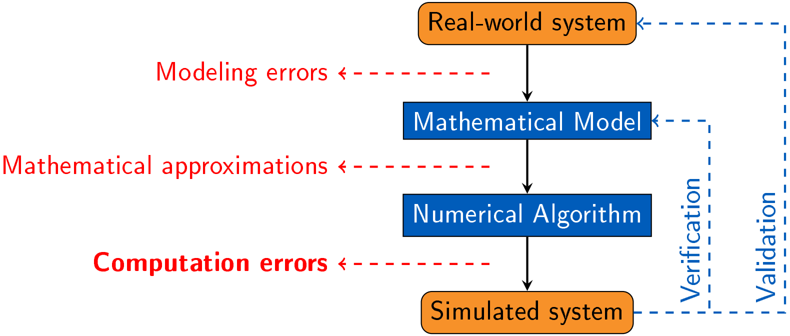
Validation

Floating-point arithmetic

- round-off errors: $a \oplus b \neq a + b$
- loss of associativity: $(a \oplus b) \oplus c \neq a \oplus (b \oplus c)$
- reproducibility issues with *e.g.* parallelization, vectorization, optimization…

Industrial context – Numerical Verification

Verification & Validation



Quantifying numerical errors: at stake

- quality of produced results (accuracy, reproducibility. . .)
- efficient use of resources (development & computing time)

Industrial context – Numerical Verification

Example: performances of an optimization problem

Initial problem formulation

$$\max_{p,v} \sum_{t\in T}\sum_{i\in I}\lambda_t p_t^i + \sum_{r\in R}\omega_r\left(v_t^r - V_0^r - \sum_{t\in T}\Gamma_t^r\right)$$

Objective functional computation

$$\begin{array}{lr}
\displaystyle\sum_{t\in T}\sum_{i\in I}\lambda_t p_t^i + \sum_{r\in R}\omega_r v_t^r & 1534019.677371745 \\
\displaystyle -\sum_{r\in R}\omega_r\left(V_0^r + \sum_{t\in T}\Gamma_t^r\right) & -1534019.677282780 \\
\hline
 & 0.000088965\underbrace{00000000000}_{\text{11 digits}}
\end{array}$$

Industrial context – Numerical Verification

Example: performances of an optimization problem

Proposed re-formulation

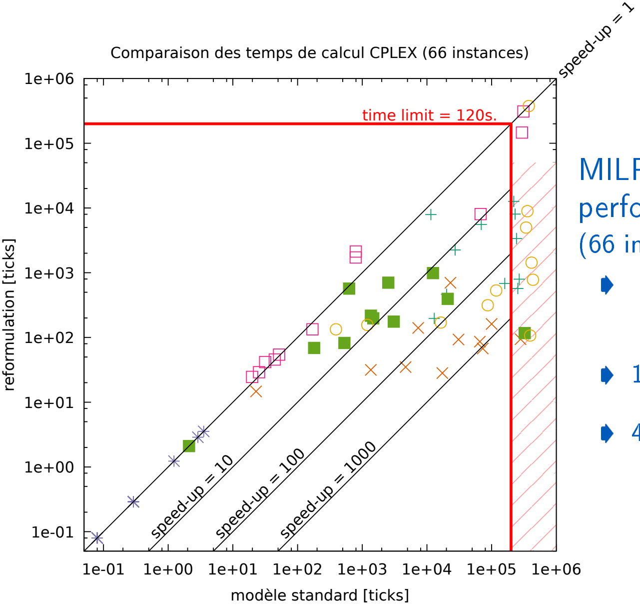
$$\left[\max_{p,v} \sum_{t\in T}\sum_{i\in I}\lambda_t p_t^i + \sum_{r\in R}\omega_r v_t^r\right] - \sum_{r\in R}\omega_r\left(V_0^r + \sum_{t\in T}\Gamma_t^r\right)$$

Objective functional computation

$$\begin{array}{lr}
\displaystyle\sum_{t\in T}\sum_{i\in I}\lambda_t p_t^i + \sum_{r\in R}\omega_r v_t^r & 1534019.677371745 \\
\displaystyle-\sum_{r\in R}\omega_r\left(V_0^r + \sum_{t\in T}\Gamma_t^r\right) & -1534019.677282780 \\
\hline
 & 0.00088965\underbrace{00000000000}_{\text{11 digits}}
\end{array}$$

Industrial context – Numerical Verification

Example: performances of an optimization problem



MILP resolution performances

(66 instances)

- 2 (3%) slowed down (×2)
- 15 (23%) unchanged
- 49 (74%) sped up (×2–1100)

Industrial context – Numerical Verification

Objectives / presentation outline

Diagnostics

- verify a code / show the presence of FP-related errors
- quantify the magnitude of issues

Debugging

- locate the origin of FP-related issues in the source code
  - unstable algorithms
  - unstable tests
- track the origin of issues during program execution
  - context of calls
  - temporal information (*e.g.* iteration number. . .)

Optimization

- use mixed-precision implementations

VERROU

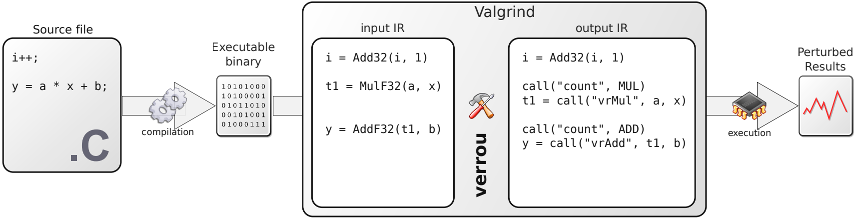
Available on github (latest version: v2.1.0)
`http://github.com/edf-hpc/verrou`

Documentation:
`http://edf-hpc.github.io/verrou/vr-manual.html`

Industrial context – Numerical Verification

Analyse dynamique du binaire avec Valgrind

```
$ valgrind --tool=verrou [VERROU_ARGS]    PROGRAM [ARGS...]
```



```
i++;

y = a * x + b;
```

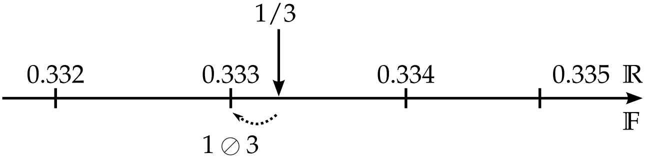
```
i = Add32(i, 1)

t1 = MulF32(a, x)


y = AddF32(t1, b)
```

```
i = Add32(i, 1)

call("count", MUL)
t1 = call("vrMul", a, x)

call("count", ADD)
y = call("vrAdd", t1, b)
```

Diagnostics: detect and assess instabilities

Verrou back-end: random rounding

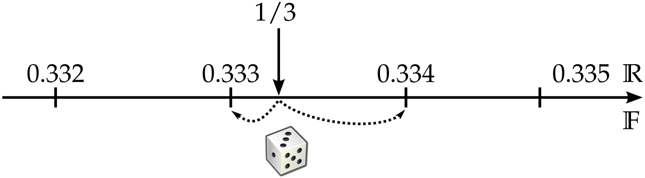
IEEE-754: nearest rounding mode



Diagnostics: detect and assess instabilities

Verrou back-end: random rounding

CESTAC/MCA: random rounding mode `--rounding-mode=random`



---

[1] J. Vignes, "A stochastic arithmetic for reliable scientific computation," *Mathematics and Computers in Simulation*, vol. 35, no. 3, 1993.

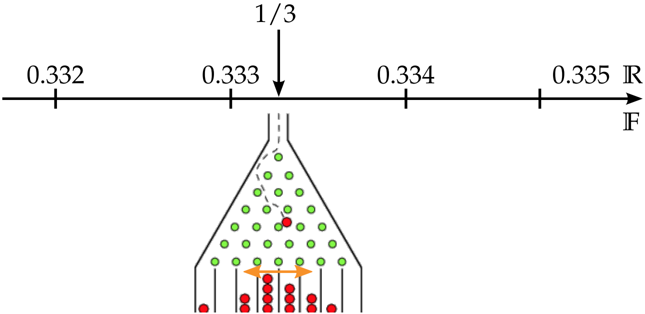
[2] J.-L. Lamotte, J.-M. Chesneaux and F. Jézéquel, "CADNA_C: A version of CADNA for use with C or C++ programs", *Computer Physics Communications*, vol. 181, no. 11, 2010.

[3] D. Stott Parker, "Monte Carlo Arithmetic: exploiting randomness in floating-point arithmetic", *Univ. California*, 1997.

Diagnostics: detect and assess instabilities

Verrou back-end: random rounding

CESTAC/MCA: random rounding mode `--rounding-mode=random`



---

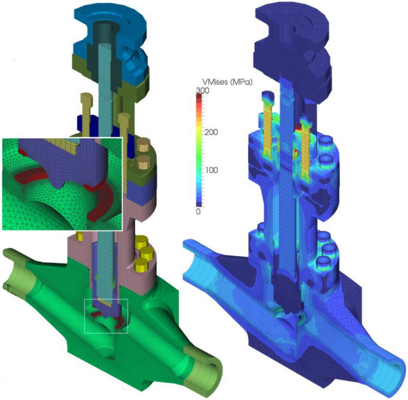
[1] J. Vignes, "A stochastic arithmetic for reliable scientific computation," *Mathematics and Computers in Simulation*, vol. 35, no. 3, 1993.

[2] J.-L. Lamotte, J.-M. Chesneaux and F. Jézéquel, "CADNA_C: A version of CADNA for use with C or C++ programs", *Computer Physics Communications*, vol. 181, no. 11, 2010.

[3] D. Stott Parker, "Monte Carlo Arithmetic: exploiting randomness in floating-point arithmetic", *Univ. California*, 1997.

Diagnostics: detect and assess instabilities

Code_aster



Mechanics

- Seismic
- Acoustic
- Thermo-mechanics

Code_Aster

- 1.2M code lines
- Fortran 90, C, Python
- thousands of test cases
- Large number of dependencies :
  - Linear solvers (MUMPS. . .)
  - Mesh generator and partitioning tools (Metis, Scotch. . .)

Goals

- understand the non-reproducibility between test computers

Diagnostics: detect and assess instabilities

Using Verrou and Random Rounding

Test case	nearest
`ssls108i`	OK
`ssls108j`	OK
`ssls108k`	OK
`ssls108l`	OK
`sdnl112a`	OK
`ssnp130a`	OK
`ssnp130b`	OK
`ssnp130c`	OK
`ssnp130d`	OK

Diagnostics: detect and assess instabilities

Using Verrou and Random Rounding

Test case	nearest	rnd_1
`ssls108i`	OK	OK
`ssls108j`	OK	OK
`ssls108k`	OK	OK
`ssls108l`	OK	OK
`sdnl112a`	OK	KO
`ssnp130a`	OK	OK
`ssnp130b`	OK	OK
`ssnp130c`	OK	OK
`ssnp130d`	OK	OK

Diagnostics: detect and assess instabilities

Using Verrou and Random Rounding

Test	Status			
case	nearest	rnd_1	rnd_2	rnd_3
`ssls108i`	OK	OK	OK	OK
`ssls108j`	OK	OK	OK	OK
`ssls108k`	OK	OK	OK	OK
`ssls108l`	OK	OK	OK	OK
`sdnl112a`	OK	KO	KO	KO
`ssnp130a`	OK	OK	OK	OK
`ssnp130b`	OK	OK	OK	OK
`ssnp130c`	OK	OK	OK	OK
`ssnp130d`	OK	OK	OK	OK

10 minutes

20 minutes each

(72 test cases)

Diagnostics: detect and assess instabilities

Using Verrou and Random Rounding

Test		Status			# common decimal digits
case	nearest	rnd_1	rnd_2	rnd_3	$C(\text{rnd}_1, \text{rnd}_2, \text{rnd}_3)$
`ssls108i`	OK	OK	OK	OK	10
`ssls108j`	OK	OK	OK	OK	10
`ssls108k`	OK	OK	OK	OK	10
`ssls108l`	OK	OK	OK	OK	9
`sdnl112a`	OK	KO	KO	KO	3
`ssnp130a`	OK	OK	OK	OK	9
`ssnp130b`	OK	OK	OK	OK	9
`ssnp130c`	OK	OK	OK	OK	9
`ssnp130d`	OK	OK	OK	OK	9

10 minutes

20 minutes each

(72 test cases)

(3 samples → lower bound for 66% of random runs with 66% confidence)

Debugging: locate issues in the source code

Using code coverage comparison: code_aster (test-cas

IEEE-754 coverage

```
120:subroutine fun1(area, a1, a2, n)
  -:    implicit none
  -:    integer :: n
  -:    real(kind=8) :: area, a1, a2
120:    if (a1 .eq. a2) then
 13:        area = a1
  -:    else
107:        if (n .lt. 2) then
107:           area = (a2-a1) / (log(a2)-log(a1))
###:        else if (n .eq.2) then
###:           area = sqrt (a1*a2)
  -:        else
###:           ! ...
  -:        endif
  -:    endif
120:end subroutine
```

Debugging: locate issues in the source code

Using code coverage comparison: code_aster (test-case `sdnl112a`)

IEEE-754 coverage

```
120:subroutine fun1(area, a1, a2, n)
  -:    implicit none
  -:    integer :: n
  -:    real(kind=8) :: area, a1, a2
120:    if (a1 .eq. a2) then
 13:        area = a1
  -:    else
107:        if (n .lt. 2) then
107:           area = (a2-a1) / (log(a2)-log(a1))
###:        else if (n .eq.2) then
###:           area = sqrt (a1*a2)
  -:        else
###:           ! ...
  -:        endif
  -:    endif
120:end subroutine
```

Stochastic Arithmetic coverage

```
120:subroutine fun1(area, a1,...
  -:    implicit none
  -:    integer :: n
  -:    real(kind=8) :: area,...
120:    if (a1 .eq. a2) then
  4:        area = a1
  -:    else
116:        if (n .lt. 2) then
116:           area = (a2-a1)...
###:        else if (n .eq.2)...
###:           area = sqrt (a...
  -:        else
###:           ! ...
  -:        endif
  -:    endif
120:end subroutine
```

Debugging: locate issues in the source code

Delta-Debugging

```
log.L                 .../aster.release
volum2_               .../aster.release
bilpla_               .../aster.release
ecrval_               .../aster.release
print_plath_          .../aster.release
classer_groupes_      .../aster.release
etupla_               .../aster.release
couhyd_pi_            .../aster.release
ecrplr_               .../aster.release
imovi_                .../aster.release
resopt_               .../aster.release
getgrp_marginal_      .../aster.release
ecrpla_               .../aster.release
fin_exec_main_        .../aster.release
decopt_pi_            .../aster.release
paraend_              .../aster.release
resopt_cnt_zones_     .../aster.release
apstop_               .../aster.release
ihyd_                 .../aster.release
impression_info_      .../aster.release
coupla_               .../aster.release
gere_print_plath_     .../aster.release
log                   .../aster.release
thepla_               .../aster.release
coutot_               .../aster.release
iprit_                .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou

→ ✓

Debugging: locate issues in the source code

Delta-Debugging

```
# log.L                .../aster.release
# volum2_              .../aster.release
# bilpla_              .../aster.release
# ecrval_              .../aster.release
# print_plath_         .../aster.release
# classer_groupes_     .../aster.release
# etupla_              .../aster.release
# couhyd_pi_           .../aster.release
# ecrplr_              .../aster.release
# imovi_               .../aster.release
# resopt_              .../aster.release
# getgrp_marginal_     .../aster.release
# ecrpla_              .../aster.release
# fin_exec_main_       .../aster.release
# decopt_pi_           .../aster.release
# paraend_             .../aster.release
# resopt_cnt_zones_    .../aster.release
# apstop_              .../aster.release
# ihyd_                .../aster.release
# impression_info_     .../aster.release
# coupla_              .../aster.release
# gere_print_plath_    .../aster.release
# log                  .../aster.release
# thepla_              .../aster.release
# coutot_              .../aster.release
# iprit_               .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou

→ ✗

Debugging: locate issues in the source code

Delta-Debugging

```
# log.L                  .../aster.release
# volum2_                .../aster.release
# bilpla_                .../aster.release
# ecrval_                .../aster.release
# print_plath_           .../aster.release
# classer_groupes_       .../aster.release
# etupla_                .../aster.release
# couhyd_pi_             .../aster.release
# ecrplr_                .../aster.release
# imovi_                 .../aster.release
# resopt_                .../aster.release
# getgrp_marginal_       .../aster.release
# ecrpla_                .../aster.release
fin_exec_main_           .../aster.release
decopt_pi_               .../aster.release
paraend_                 .../aster.release
resopt_cnt_zones_        .../aster.release
apstop_                  .../aster.release
ihyd_                    .../aster.release
impression_info_         .../aster.release
coupla_                  .../aster.release
gere_print_plath_        .../aster.release
log                      .../aster.release
thepla_                  .../aster.release
coutot_                  .../aster.release
iprit_                   .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou

→ ✗

Debugging: locate issues in the source code

Delta-Debugging

```
# log.L                  .../aster.release
# volum2_                .../aster.release
# bilpla_                .../aster.release
# ecrval_                .../aster.release
# print_plath_           .../aster.release
# classer_groupes_       .../aster.release
# etupla_                .../aster.release
couhyd_pi_               .../aster.release
ecrplr_                  .../aster.release
imovi_                   .../aster.release
resopt_                  .../aster.release
getgrp_marginal_         .../aster.release
ecrpla_                  .../aster.release
fin_exec_main_           .../aster.release
decopt_pi_               .../aster.release
paraend_                 .../aster.release
resopt_cnt_zones_        .../aster.release
apstop_                  .../aster.release
ihyd_                    .../aster.release
impression_info_         .../aster.release
coupla_                  .../aster.release
gere_print_plath_        .../aster.release
log                      .../aster.release
thepla_                  .../aster.release
coutot_                  .../aster.release
iprit_                   .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou

→ ✓

Debugging: locate issues in the source code

Delta-Debugging

```
log.L                 .../aster.release
volum2_               .../aster.release
bilpla_               .../aster.release
ecrval_               .../aster.release
print_plath_          .../aster.release
classer_groupes_      .../aster.release
etupla_               .../aster.release
# couhyd_pi_          .../aster.release
# ecrplr_             .../aster.release
# imovi_              .../aster.release
# resopt_             .../aster.release
# getgrp_marginal_    .../aster.release
# ecrpla_             .../aster.release
fin_exec_main_        .../aster.release
decopt_pi_            .../aster.release
paraend_              .../aster.release
resopt_cnt_zones_     .../aster.release
apstop_               .../aster.release
ihyd_                 .../aster.release
impression_info_      .../aster.release
coupla_               .../aster.release
gere_print_plath_     .../aster.release
log                   .../aster.release
thepla_               .../aster.release
coutot_               .../aster.release
iprit_                .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou

→ ✗

Debugging: locate issues in the source code

Delta-Debugging

```
log.L                 .../aster.release
volum2_               .../aster.release
bilpla_               .../aster.release
ecrval_               .../aster.release
print_plath_          .../aster.release
classer_groupes_      .../aster.release
etupla_               .../aster.release
# couhyd_pi_          .../aster.release
ecrplr_               .../aster.release
imovi_                .../aster.release
resopt_               .../aster.release
getgrp_marginal_      .../aster.release
ecrpla_               .../aster.release
fin_exec_main_        .../aster.release
# decopt_pi_          .../aster.release
paraend_              .../aster.release
resopt_cnt_zones_     .../aster.release
apstop_               .../aster.release
# ihyd_               .../aster.release
impression_info_      .../aster.release
coupla_               .../aster.release
gere_print_plath_     .../aster.release
log                   .../aster.release
thepla_               .../aster.release
# coutot_             .../aster.release
# iprit_              .../aster.release
```

- Delta-Debugging [A. Zeller, 1999]
- relies on ability to restrict the scope of instrumentation/perturbations induced by Verrou
- Inputs :
  - run script
  - comparison script
- Output:
  - “unstable” code parts
- Also works at the source line granularity:
  - if the code was compiled with -g

Debugging: locate issues in the source code

Delta-Debugging on code_aster (test-case `sdnl112a`)

```
      do 60 jvec = 1, nbvect
         do 30 k = 1, neq
            vectmp(k)=vect(k,jvec)
30       continue
         if (prepos) call mrconl('DIVI', lmat, 0, 'R', vectmp,1)
         xsol(1,jvec)=xsol(1,jvec)+zr(jvalms-1+1)*vectmp(1)
         do 50 ilig = 2, neq
            kdeb=smdi(ilig-1)+1
            kfin=smdi(ilig)-1
            do 40 ki = kdeb, kfin
               jcol=smhc(ki)
               xsol(ilig,jvec)=xsol(ilig,jvec) + zr(jvalmi-1+ki) * vectmp(jcol)
               xsol(jcol,jvec)=xsol(jcol,jvec) + zr(jvalms-1+ki) * vectmp(ilig)
40          continue
            xsol(ilig,jvec)=xsol(ilig,jvec) + zr(jvalms+kfin) * vectmp(ilig)
50       continue
         if (prepos) call mrconl('DIVI', lmat, 0, 'R', xsol(1, jvec),1)
60    continue
```

Optimization for mixed precision

Verrou back-end: precision reduction

- All high-precision values are cast to single precision before performing arithmetic operations
  - emulates the use of low-precision arithmetic
  - . . . but not the performance boost.
- Currently implemented only for double→single (`--rounding-mode=float`)
  - can be generalized to all precision reductions (*e.g* single → half)
  - can not emulate higher precision (memory problem)
- Can be combined with Delta-Debugging
  - find which code parts can be downgraded to lower precision

---

[1] A. Dawson and P. D. Düben, "rpe v5: an emulator for reduced floating-point precision in large numerical simulations", *Geoscientific Model Development*, 2017.

Wrap-up

Verrou as a tool to help with FP issues

Diagnostics

- ☼ show the presence of FP-related errors (random-rounding back-end)
- ⛅ quantify the magnitude of issues (post-processing)

Debugging

- ⛅ locate the origin of FP-related issues in the source code
  - ☼ unstable algorithms (Delta-Debugging)
  - ⛅ unstable tests (code coverage analysis)
- 🌧 track the origin of issues during program execution
  - ▶ context of calls
  - ▶ temporal information (*e.g.* iteration number. . .)

Optimization

- ☁ emulate mixed-precision implementations (reduced precision back-end)
- ➧ re-use debugging features (Delta-Debugging)

Outlooks

Interflop

- Verrou is no silver bullet
  - multiply techniques & tools

Interflop (toolbox)

Common interface for Verificarlo & Verrou (and anyone interested!)

- share Stochastic Arithmetic back-ends
- share accompanying tools (Delta-Debugging. . .)
- improve performance of instrumentation front-ends

Interflop (consortium)

- Explore different analysis methods and the links between them
  - Stochastic Arithmetic
  - Interval Arithmetic & Affine Forms

Thank you !

Questions ?

Get Verrou on github:
http://github.com/edf-hpc/verrou

Documentation:
http://edf-hpc.github.io/verrou/vr-manual.html

Relevant references I

Jean-Marie Chesneaux and Jean Vignes, *On the robustness of the cestac method*, C. R. Acad.Sci. Paris **1** (1988), 855–860.

A. Dawson and P. D. Düben, *rpe v5: an emulator for reduced floating-point precision in large numerical simulations*, Geoscientific Model Development **10** (2017), no. 6, 2221–2230.

Christophe Denis, Pablo de Oliveira Castro, and Eric Petit, *Verificarlo: checking floating point accuracy through Monte Carlo Arithmetic*, 23rd IEEE Internatinal Symposium on Computer Arithmetic (ARITH'23), 2016.

François Févotte and Bruno Lathuilière, *VERROU: Assessing Floating-Point Accuracy Without Recompiling*, `https://hal.archives-ouvertes.fr/hal-01383417`, October 2016.

Relevant references II

François Févotte and Bruno Lathuilière, *Studying the numerical quality of an industrial computing code: A case study on code_aster*, 10th International Workshop on Numerical Software Verification (NSV) (Heidelberg, Germany), July 2017, pp. 61–80.

Stef Graillat, Fabienne Jézéquel, and Romain Picot, *Numerical validation of compensated algorithms with stochastic arithmetic*, Applied Mathematics and Computation **329** (2018), 339 – 363.

Fabienne Jézéquel, Jean-Marie Chesneaux, and Jean-Luc Lamotte, *A new version of the CADNA library for estimating round-off error propagation in Fortran programs*, Computer Physics Communications **181** (2010), no. 11, 1927–1928.

William Kahan, *How futile are mindless assessments of roundoff in floating-point computations?*, `https://people.eecs.berkeley.edu/~wkahan/Mindless.pdf`, 2006.

Relevant references III

- Jean-Luc Lamotte, Jean-Marie Chesneaux, and Fabienne Jézéquel, *CADNA_C: A version of CADNA for use with C or C++ programs*, Computer Physics Communications **181** (2010), no. 11, 1925–1926.
- Devan Sohier, Pablo De Oliveira Castro, François Févotte, Bruno Lathuilière, Eric Petit, and Olivier Jamond, *Confidence Intervals for Stochastic Arithmetic*, preprint, `https://hal.archives-ouvertes.fr/hal-01827319`.
- Douglas Stott Parker, *Monte Carlo arithmetic: exploiting randomness in floating-point arithmetic*, Tech. Report CSD-970002, University of California, Los Angeles, 1997.
- Jean Vignes, *A stochastic arithmetic for reliable scientific computation*, Mathematics and Computers in Simulation **35** (1993), 233–261.
- Andreas Zeller, *Yesterday, My Program Worked. Today, It Does Not. Why?*, SIGSOFT Softw. Eng. Notes **24** (1999), no. 6, 253–267.

Annexes

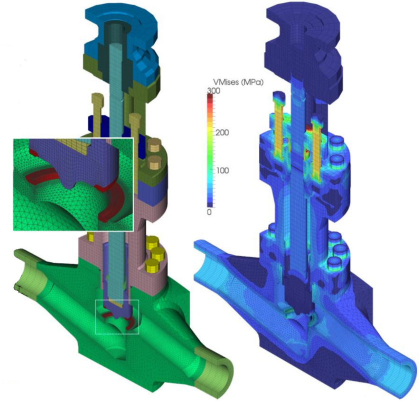
Additional slides

Case study on ACTS: emulation of reduced precision + NaN detection

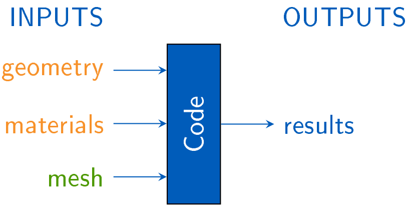
```
$ valgrind --tool=verrou --rounding-mode=float --exclude=excludes.ex --demangle=no --trace-children=yes --num-callers=50 \
>          ctest -V -R "BFieldMapUtils"
                                                                                 [...]
==1863== NaN:
==1863==    at 0x5847E7F: _ZN5Eigen8internal4pmulIDv2_dEET_RKS3_S5_ (emmintrin.h:271)
==1863==    by 0x585B570: _ZNK5Eigen8internal17scalar_product_opIddE8packetOpIDv2_dEEKT_RS6_S7_ (BinaryFunctors.h:89)
==1863==    by 0x59A31C9: _ZNK5Eigen8internal16binary_evaluatorINS_13CwiseBinaryOpINS0_17scalar_product_opIddEEKNS_14
                          CwiseNullaryOpINS0_18scalar_constant_opIdEEKNS_6MatrixIdLi2ELi1ELi0ELi2ELi1EEEEEESA_EENS0_10
                          IndexBasedESE_ddE6packetILi16EDv2_dEET0_ll (CoreEvaluators.h:727)
                                                                                 [...]
==1863==    by 0x5BDE2D4: _ZN5Eigen6MatrixIdLi2ELi1ELi0ELi2ELi1EEaSINS_13CwiseBinaryOpINS_8internal13scalar_sum_opIdd
                          EEKNS3_INS4_17scalar_product_opIddEEKNS_14CwiseNullaryOpINS4_18scalar_constant_opIdEEKS1_EE
                          SC_EESG_EEEERS1_RKNS_9DenseBaseIT_EE (Matrix.h:225)
==1863==    by 0x5BDAD82: _ZN4Acts6detail16interpolate_implIN5Eigen6MatrixIdLi2ELi1ELi0ELi2ELi1EEES4_St5arrayIdLm2EES
                          6_Lm1ELm4EE3runERKS4_RKS6_SB_RKS5_IS4_Lm4EE (interpolation_impl.hpp:133)
==1863==    by 0x5BD59E8: _ZN4Acts11interpolateIN5Eigen6MatrixIdLi2ELi1ELi0ELi2ELi1EEELm4ES3_St5arrayIdLm2EES5_vEET_R
                          KT1_RKT2_RKT3_RKS4_IS6_XT0_EE (Interpolation.hpp:95)
                                                                                 [...]
==1863==    by 0x4F6D54:  _ZNK4Acts21InterpolatedBFieldMap11FieldMapperILj2ELj2EE8getFieldERKN5Eigen6MatrixIdLi3ELi1EL
                          i0ELi3ELi1EEE (InterpolatedBFieldMap.hpp:166)
==1863==    by 0x477030:  _ZN4Acts4Test15bfield_creation11test_methodEv (BFieldMapUtilsTests.cpp:88)
==1863==    by 0x474767:  _ZN4Acts4TestL23bfield_creation_invokerEv (BFieldMapUtilsTests.cpp:25)
==1863==    by 0x549B9B:  _ZN5boost6detail8function22void_function_invoker0IPFvvEvE6invokeERNS1_15function_bufferE (fu
                          nction_template.hpp:118)
                                                                                 [...]
==1863==    by 0x43F2FE:  _ZN5boost9unit_test9framework3runEmb (framework.ipp:1629)
==1863==    by 0x463F10:  _ZN5boost9unit_test14unit_test_mainEPFPNS0_10test_suiteEiPPcEiS4_ (unit_test_main.ipp:247)
==1863==    by 0x4648CB:  main (unit_test_main.ipp:303)
                                                                                 [...]
Running 12 test cases...
acts-core/Tests/Utilities/BFieldMapUtilsTests.cpp(105): error: in "bfield_creation": difference{-nan} between
        value2_rz.perp(){-nan} and bField2_rz.perp(){8} exceeds 1e-09%
```

Additional slides

V&V process: ad-hoc numerical instability detection methods



Physical input: affects the result
Simulation parameter: should be neutral



INPUTS

OUTPUTS

geometry

materials

mesh

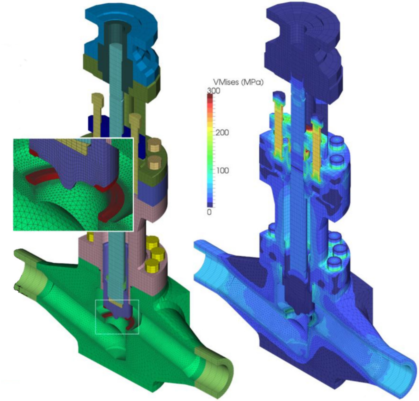
Code

results

- Idea: measure the sensitivity of the results w.r.t "neutral" parameters
  - ☼ easy to do
  - 🌧 *ad hoc*, no localization

Additional slides

V&V process: ad-hoc numerical instability detection methods



Physical input: affects the result
Simulation parameter: should be neutral

INPUTS

OUTPUTS

geometry →

materials →

mesh →

compiler →

hardware specification →

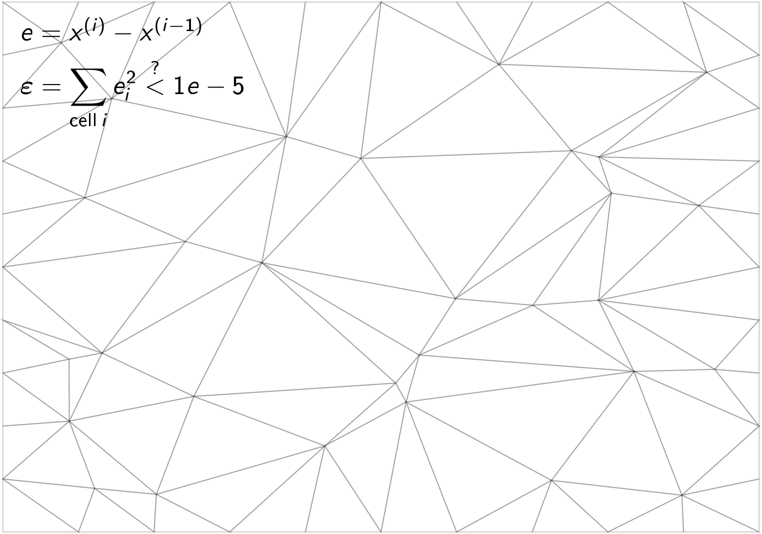
. . . →

Code

→ results

Additional slides

Example 1: failing computation in free surface hydraulics (Telemac 2D)

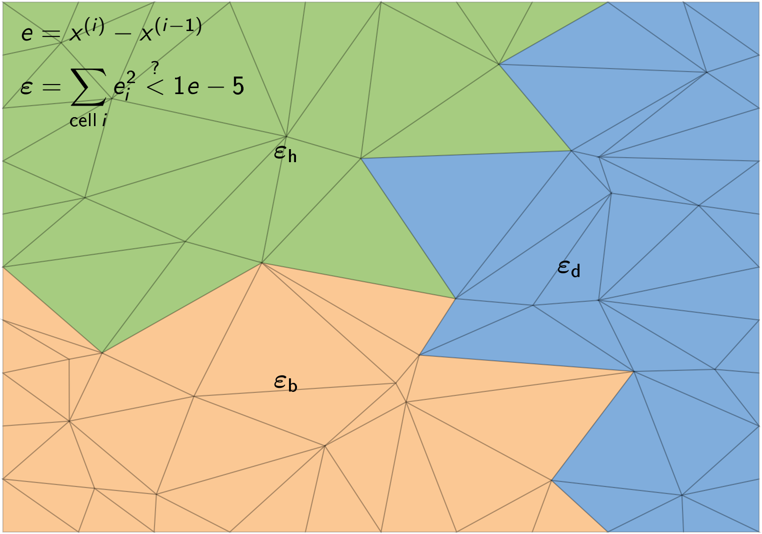


$$e = x^{(i)} - x^{(i-1)}$$

$$\varepsilon = \sum_{\text{cell } i} e_i^2 \overset{?}{<} 1e-5$$

Additional slides

Example 1: failing computation in free surface hydraulics (Telemac 2D)

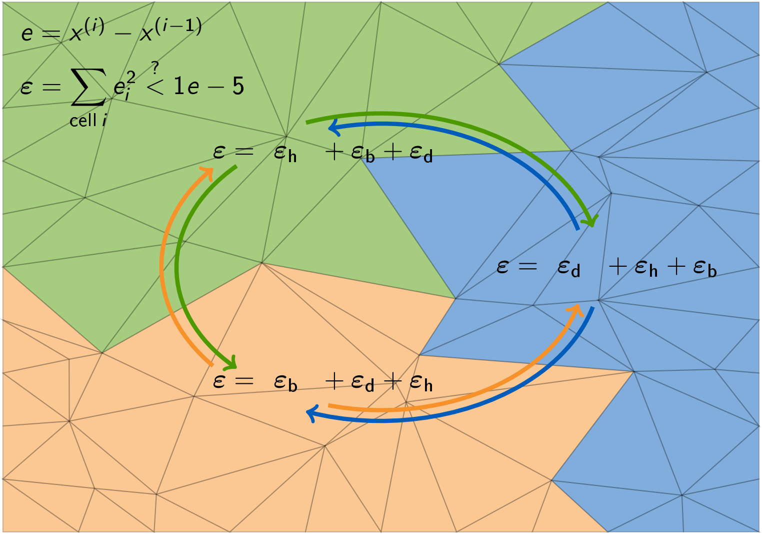


$$e = x^{(i)} - x^{(i-1)}$$

$$\varepsilon = \sum_{\text{cell } i} e_i^2 \overset{?}{<} 1e-5$$

Additional slides

Example 1: failing computation in free surface hydraulics (Telemac 2D)



$$e = x^{(i)} - x^{(i-1)}$$

$$\varepsilon = \sum_{\text{cell } i} e_i^2 \overset{?}{<} 1e-5$$

$$\varepsilon = \varepsilon_{\mathsf{h}} + \varepsilon_{\mathsf{b}} + \varepsilon_{\mathsf{d}}$$

$$\varepsilon = \varepsilon_{\mathsf{d}} + \varepsilon_{\mathsf{h}} + \varepsilon_{\mathsf{b}}$$

$$\varepsilon = \varepsilon_{\mathsf{b}} + \varepsilon_{\mathsf{d}} + \varepsilon_{\mathsf{h}}$$