VeriTracer: Context-enriched tracer for floating-point arithmetic analysis

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Yohan Chatelain[1,5] Pablo de Oliveira Castro[1,5] Eric Petit[2,5] David Defour[3]
Jordan Bieder[4,5] Marc Torrent[4,5]

[1]Université de Versailles Saint-Quentin-en-Yvelines (UVSQ)
[2]Intel
[3]Université de Perpignan Via Domitia (UPVD)
[4]CEA, DAM, DIF
[5]Exascale Computing Research (ECR)

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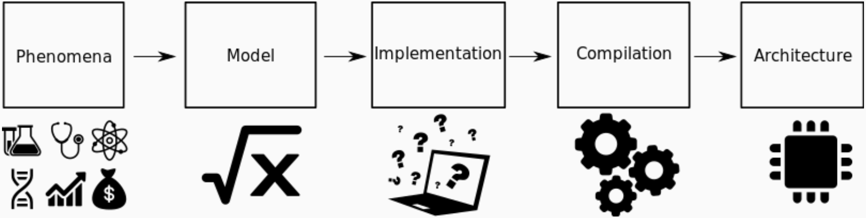
Introduction

Context

Building fast and robust applications for HPC is a complex task !



- At each step, numerical bugs can be introduced

Objective: Tools to track and analyze numerical bugs

Existing tools

	Method	Name	Implementation
Debugging	Stochastic Arithmetic	CADNA [9] VERROU [5] Verificarlo [4]	CESTAC/DSA (library) CESTAC (Valgrind) MCA (LLVM)
	Extended Precision (EP)	HPC Craft [10] FpDebug [3] Herbgrind [15]	Exponent comparison (DynInst) MPFR (Valgrind) MPFR (Valgrind)

	Name	Method	Mixed-Precision	Any-Precision
Optimization	Verificarlo [4]	MCA (User specific)	✓	✓
	HPC Craft [10]	Bitmask (ref value)	✓	✓
	Promise [8]	CESTAC/DSA ($\Delta - debug$)	✓	
	Precimonious [14]	EP ($\Delta - debug$)	✓	
	Herbie [12]	EP (Rewriting)		

Muller's sequence[2] overview

$$u_n = \left\{ \begin{array}{l} u_0 = 2 \\ u_1 = -4 \\ u_{n+1} = 111 - \dfrac{1130}{u_n} + \dfrac{3000}{u_n u_{n-1}} \end{array} \right\} \lim_{n\to\infty} u_n =$$

exact solution

6

100

finite precision

CADNA	Verificarlo
u_{30} mean: 100 significant digits: 16	u_{30} mean: 100 significant digits: 16

Stochastic methods execute several samples by introducing random errors

Muller's sequence[2] overview

exact solution

6

$$u_n = \left\{ \begin{array}{l} u_0 = 2 \\ u_1 = -4 \\ u_{n+1} = 111 - \dfrac{1130}{u_n} + \dfrac{3000}{u_n u_{n-1}} \end{array} \right\} \quad \lim_{n \to \infty} u_n =$$

100

finite precision

~~CADNA~~	~~Verificarlo~~
~~u_{30}~~	~~u_{30}~~
~~mean: 100~~	~~mean: 100~~
~~significant digits: 16~~	~~significant digits: 16~~

Without an exact solution

- Only checking the final result may leads to wrong conclusions !

Current challenges

Existing tools explore the spatial dimension of numerical computations:

- which variable or operation is imprecise
- which function can be switched into lower precision
- but programs have different numerical requirements over time

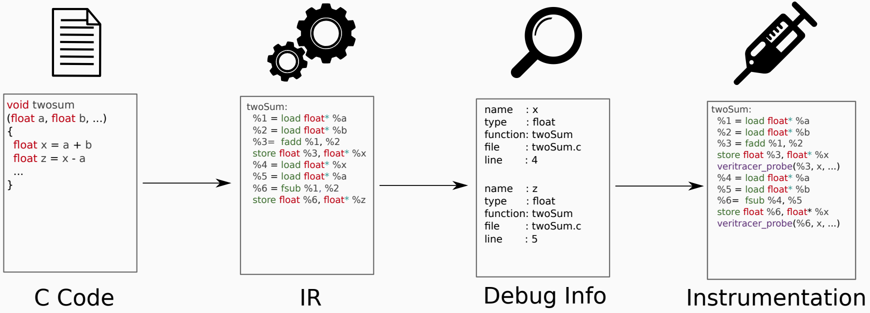
$\Rightarrow$ **Need to explore the temporal dimension**

Veritracer

Instrumentation

Veritracer LLVM pass

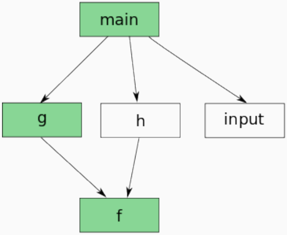
- Accepts any source code accepted by the LLVM frontend
- Transforms into an LLVM Intermediate Representation
- Searches debug information through LLVM IR
- Instruments the IR code with veritracer probes

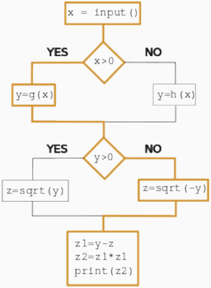


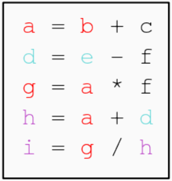
Information Flow Analysis

Ansychronous analysis

- Veritracer works in an asynchronous way
- Information flow is necessary for gathering the traces
- Three levels of granularities are analyzed:
  - **Context Analysis**: considers the context of a function call
  - **Control-Flow Analysis**: considers the flow path taken
  - **Data-Flow Analysis**: considers the dependencies between variables







Pinpointing relevant function

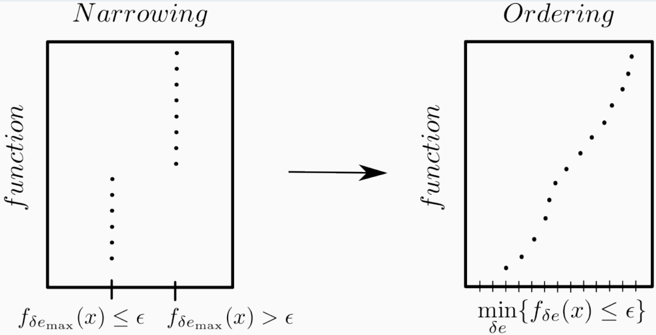
Narrowing the search space

To narrow the search space, we:

Scan functions with FP values

Narrow the set by removing non-contributing functions $f_{\delta e_{\max}}(x) \leq \epsilon$,

Order functions by *numerical stress resistance* $\min_{\delta e}\{f_{\delta e_{\min}} \leq \epsilon\}$



Implementation

Extends verificarlo to

- Trace the precision of FP variables over time
- Provide contextual information on traced variables
  - Current version implements Context Analysis
  - Inserts call to `backtrace()` (GNU C library)
  - Analyzes backtraces to detect flow divergences
- All in an automatic way

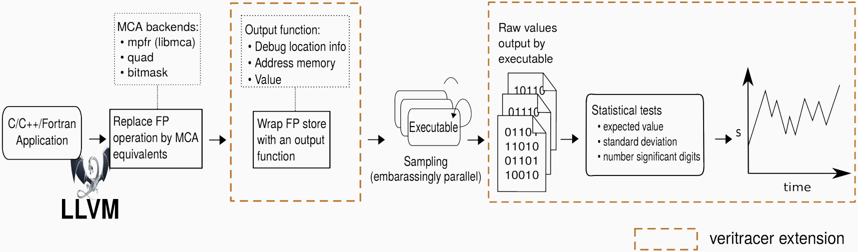


Figure 1: Veritracer's workflow

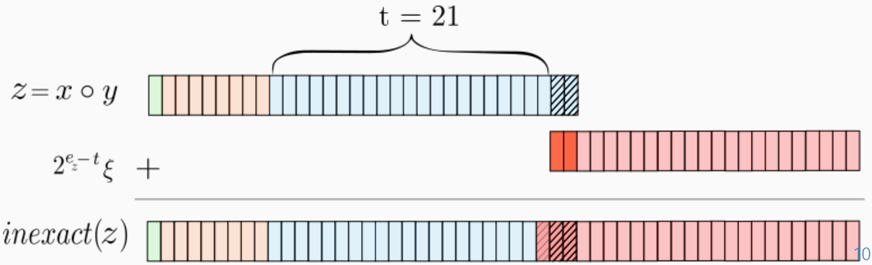
Monte Carlo Arithmetic (MCA) [13]

$\text{inexact}(x) = x + \beta^{e_x - t}\xi$

- e_x is the magnitude of x
- t the virtual precision
- ξ a random variable between $\left]-\frac{1}{2}, \frac{1}{2}\right[$

Random Rounding mode

- $RR(x \circ y) = inexact(x \circ y), \ \circ \in \{+, -, \times, \backslash\}$



Experiments

Muller's sequence with veritracer

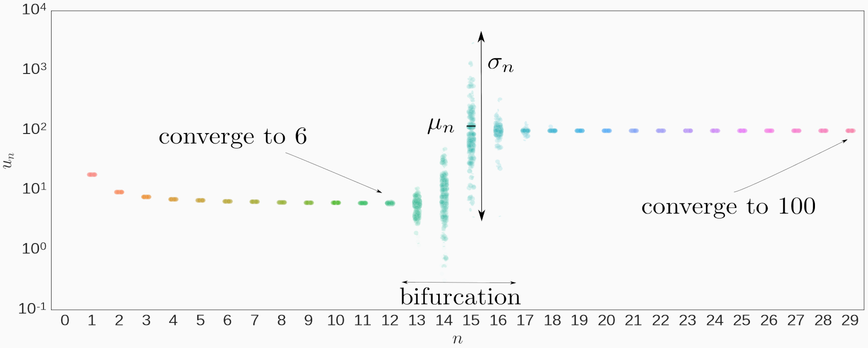


Figure 2: Muller's sequence evaluation over 500 samples with veritracer. The sequence converges to 6 before bifurcating and then converges to 100.

- Estimate the number of significant digits by using N samples
  $\tilde{s} = -\log_{10}\left(\frac{\tilde{\sigma}}{\tilde{\mu}}\right)$
- $\tilde{\mu}$: empirical mean and $\tilde{\sigma}$: empirical standard deviation

ABINIT [7]

- Calculates observable properties of materials (optical, mechanical, vibrational)
- Works on any chemical composition (molecules, nanostructures, solids)

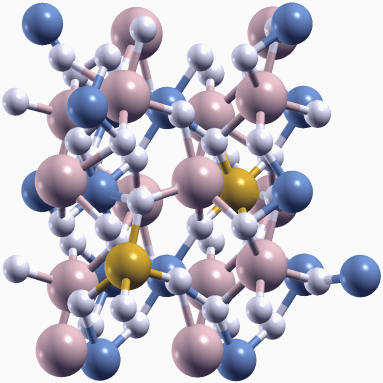
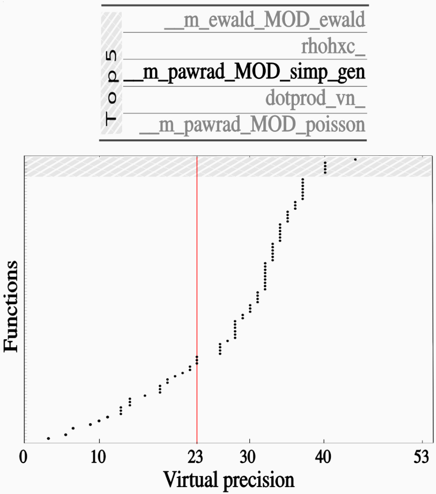


Figure 3: Sound velocity calculation in an earth mantle component ($MgSiO_3$ perovskyte with Al impurities) [1]

Ordering the search space



Functions below 23bits

- are more resistant
- can potentially be changed to single precision

Functions above 23bits

- are less resistant
- require further analyses

Interesting function among the top 5

`__m_pawrad_MOD_simp_gen`

Simp_gen: Evaluation with Veritracer

Computes an integral by Simpsons' rule over a generalized 1D-grid

- Can be seen as a dot product

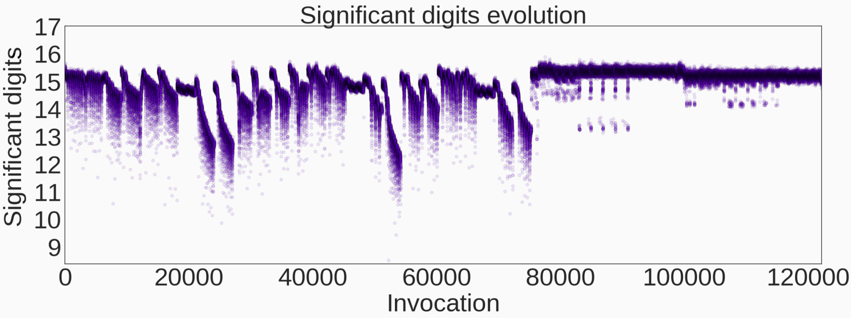
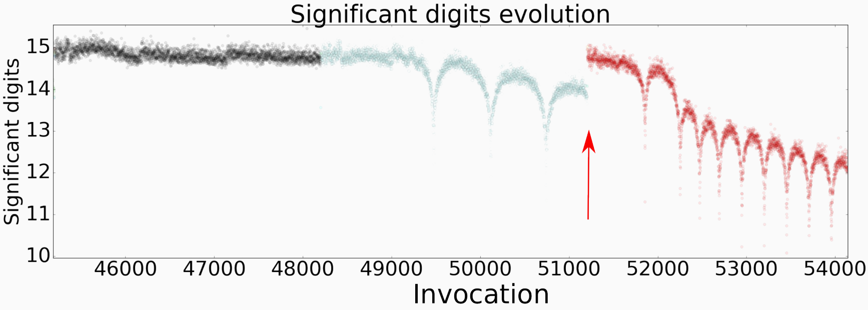


Figure 4: Evolution of the value returned by simp_gen with $t = 53$ in Random Rounding mode with 24 samples in parallel on the **CINES Occigen** cluster (2106 nodes x2 Intel 12-Cores (E5-2690V3@2.6 GHz))

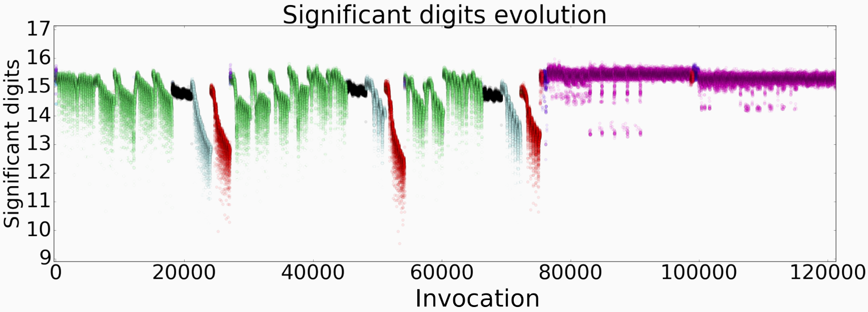
Simp_gen: the importance of the context analysis

- Colors represent the different CSPs
- Red arrow seems to point an enhancement of the quality ...
- ... but red points come from another context

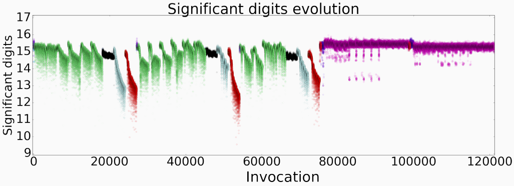


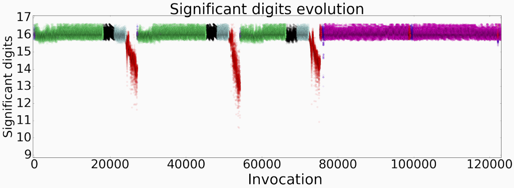
Simp_gen: the importance of the context analysis

- Colors represent the different CSPs
- Red arrow seems to point an enhancement of the quality ...
- ... but red points come from another context
- Hence the importance of separating contexts



Simp_gen: A compensated version





Simp_gen: Altered version

- Can be seen a dot product
- Replaces by a compensated version Dot2 [11]
- Implemented with `libeft` [6]
- The precision of 30/31 CSPs is improved
- 1 CSP has a low precision due to reentrance of the error

Conclusion

Conclusion

Veritracer is a numerical debugger/optimizer which

- Automatically instruments codes through the verificarlo framework
- Automatically plots the temporal numerical quality of variables
- Provides contextual information

Veritracer can be used on real world HPC applications to

- Detect the numerical sensitivity of functions
- Classify functions according to their numerical sensitivity
- Observe the numerical behavior of functions over time

Thank you for your attention

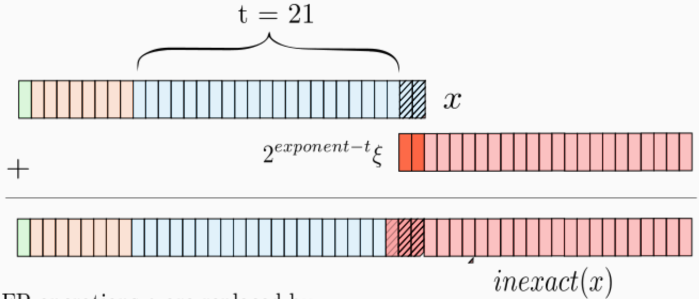
Available on github:

`github.com/verificarlo/verificarlo`
`github.com/verificarlo/verificarlo/tree/veritracer`

Random Rounding mode (MCA)

Monte Carlo Arithmetic [parker1997monte]

$$inexact(x) = x + 2^{exponenent-t}\xi, \quad \xi \in [-\frac{1}{2}, \frac{1}{2}], \quad \text{t virtual precision}$$



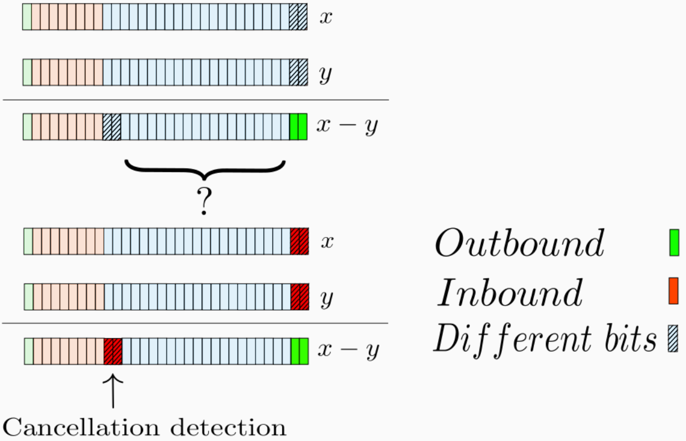
FP operations $\circ$ are replaced by:

$$RR(x \circ y) = round(inexact(x \circ y))$$

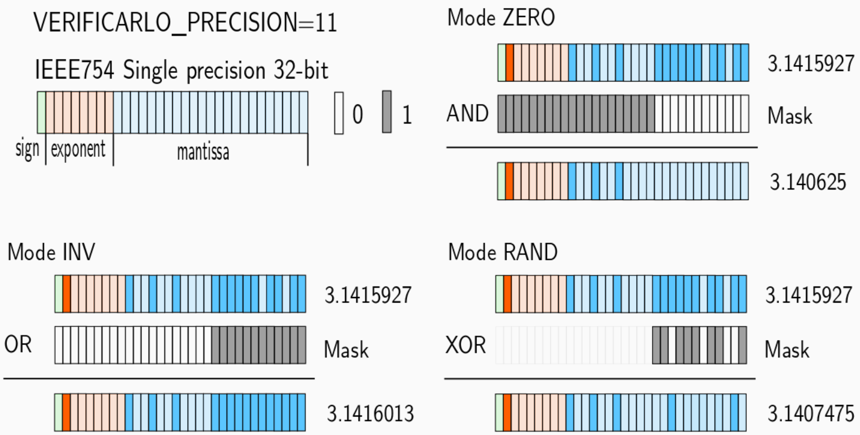
Full MCA mode

$$x \sim y$$

$$mca(x) = round(inexact(inexact(x) - inexact(y)))$$



Bitmask backend



Errors propagation

```
subroutine pawpsp_calc(...)
...
if (testval) then
    ...
    call simp_gen(qq, nhat, vale_mesh)
    qq=zion/four_pi-qq
end if

call atompaw_shpfun(..., intg, nhat)

♠ nhat(1:msz)=qq*nhat(1:msz)
tnvale(1:msz)=tnvale(1:msz)+nhat(1:msz)
...
call pawpsp_cg(..., tnvale, ...)
```

```
subroutine atompaw_shpfun(..., norm, shapefunc)
...
simp_gen(norm,r2k,mesh)
norm=one/norm
shapefunc(1:ishp)=shapefunc(1:ishp)*norm
```

out

inout

```
subroutine pawpsp_cg(..., nr, ...)
...
do ir=1,mesh_size
    rnr(ir)=radmesh%rad(ir)*nr(ir)
end do
...
do ir=1,mesh_size
    if (abs(rnr(ir))>1.d-20)
        ff(ir)=sin(arg*radmesh%rad(ir))*rnr(ir)
end do
...
♣ call simp_gen(r1torm, ff, radmesh)
```

out

```
subroutine simp_gen(intg, func, radmesh)
...
nn=radmesh%int_meshsz
simp=zero
do i=1,nn
    simp=simp+func(i)*radmesh%simfact(i)
end do
...
intg=simp+resid
end subroutine
```

Veritracer: the LLVM IR

```
void twoSum
(double a, double b, double *x_ptr, double *err_ptr) {
  double x = a + b;
  double z = x - a;
  double e = (a - (x - z)) + (b - z);
  *x_ptr = x;
  *err_ptr = e;
}
```

```
define void @twoSum
(float %a, float %b, float* %x_ptr, float* %e_ptr)
{
  %5 = load float* %a          ;
  %6 = load float* %b          ;
  %7 = fadd float %5, %6       ;     a+b
  store float %7, float* %x    ; x = a+b
  %8 = load float* %x          ;
  %9 = load float* %a          ;
  %10 = fsub float %8, %9      ;     x-a
  store float %10, float* %z   ; z = x-a
  %11 = load float* %a         ;
  %12 = load float* %x         ;
  %13 = load float* %z         ;
  %14 = fsub float %12, %13    ;     x-z
  %15 = fsub float %11, %14    ;     a-(x-z)
  %16 = load float* %b         ;
  %17 = load float* %z         ;
  %18 = fsub float %16, %17    ;     b-z
  %19 = fadd float %15, %18    ;     a-(x-z)+(b-z)
  store float %19, float* %e   ; e = a-(x-z)+(b-z)
  %20 = load float* %x         ;
  %21 = load float** %3        ;
  store float %20, float* %21 ; *x_ptr = x
  %22 = load float* %e         ;
  %23 = load float** %4,       ;
  store float %22, float* %23 ; *e_ptr = e
  ret void
}
```

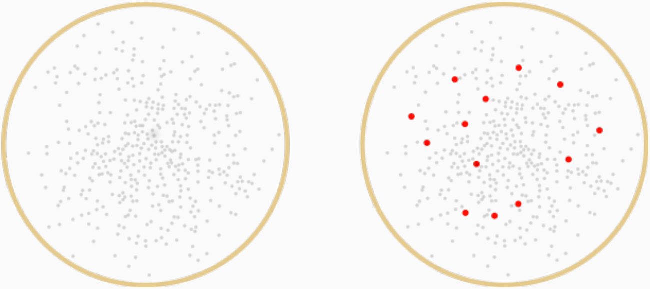
```
define void @twoSum
(float %a, float %b, float* %x_ptr, float* %err_ptr)
{
  %1 = fadd float %a, %b        ; a+b     (x)
  %2 = fsub float %1, %a        ; (a+b)-a (z)
  %3 = fsub float %1, %2        ; x-z
  %4 = fsub float %a, %3        ; a-(x-z)
  %5 = fsub float %b, %2        ; b-z
  %6 = fadd float %5, %4        ; (b-z)+(a-(x-z))
  store float %1, float* %x_ptr ; *x_ptr = x
  store float %6, float* %e_ptr ; *e_ptr = e
  ret void
}
```

Reducing the search space

Instrumenting one function of the program at a time

- Executes each version with the maximal MCA error
- Compares the MCA computed value with the reference:

  Different : the function is tagged as critical
  Identical : the function is tagged not critical



2952 function ⇒ 88 functions
Reduces the search space by ×30

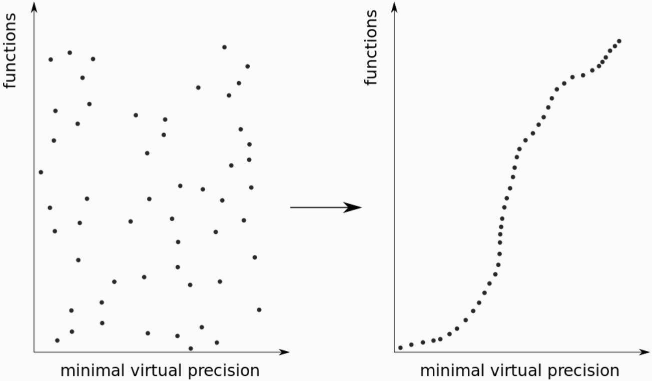
Ordering the search space

Problem

Functions do not have the same numerical behavior: some functions are less sensitive to numerical errors than others

Idea

Classifying functions according to their numerical stress resistance



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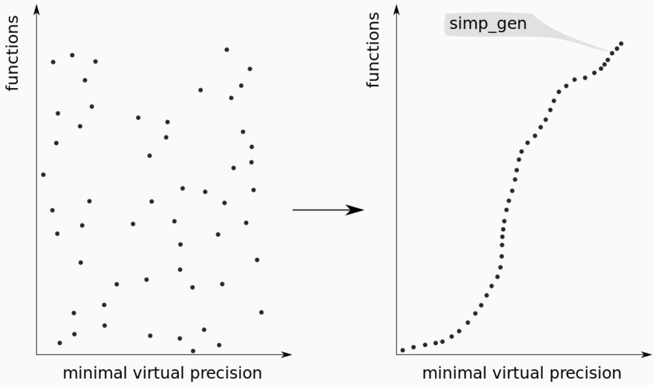

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