Workpackage 5:
High Performance Mathematical Computing

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Second OpenDreamKit Project review

Luxembourg, October 30, 2018

High performance mathematical computing

Mathematical computing

Computing with a large variety of objects

- $\mathbb{Z}, \mathbb{Q}, \mathbb{Z}/p\mathbb{Z}, \mathbb{F}_q,$ 175417188143890121646322

for applications where all digits matter.

High performance mathematical computing

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- Polynomials over $\mathbb{Z}, \mathbb{Q}, \mathbb{Z}/p\mathbb{Z}, \mathbb{F}_q,$ $\frac{2}{5}x^3 + x^2 - \frac{1}{19}x + 2$

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- Matrices of polynomials over $\mathbb{Z}, \mathbb{Q}, \mathbb{Z}/p\mathbb{Z}, \mathbb{F}_q,$ $\begin{bmatrix} 3x^2+3 & 2x^2+3 \\ 4x^2+1 & x^2+4x+4 \end{bmatrix}$

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$$\frac{3q^2-q^5}{q^5+2q^4+3q^3+3q^2+2q+1} \quad + \quad \frac{2q}{q^4+q^3+2q^2+q+1}$$

- Tree algebras

for applications where all digits matter.

High performance mathematical computing

Need for High performance: applications where size is crucial:

Experimental maths: testing conjectures

- larger instances give higher confidence

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Algebraic cryptanalysis: security = computational difficulty

- ▶ key size determined by the largest solvable problem

Example

Breaking RSA by integer factorization: $n = pq$. Last record:

- ▶ n of 768 bits
- ▶ linear algebra in dimension $192\,796\,550$ over $\mathbb{F}_2$ (105Gb)
- ▶ About 2000 CPU years

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3D data analysis, shape recognition:

- ▶ via persistent homology
- ▶ large sparse matrices over $\mathbb{F}_2$, $\mathbb{Z}$

Goal: delivering high performance to maths users

Systems : GAP PARI/GP SageMath Singular

Components : FLINT MPIR LinBox PPL NumPy

Goal: delivering high performance to maths users

Harnessing modern hardware ⤳ parallelisation

- in-core parallelism (SIMD vectorisation)
- multi-core parallelism
- distributed computing: clusters, cloud

Systems : GAP PARI/GP SageMath Singular

Components : FLINT MPIR LinBox PPL NumPy

Architectures : SIMD Multicore server HPC cluster Cloud

Goal: delivering high performance to maths users

Languages

- Computational Maths software uses high level languages (e.g. Python)
- High performance delivered by languages close to the metal (C, assembly)

⤳ compilation, automated optimisation

Systems : GAP   PARI/GP   SageMath   Singular

Components : FLINT   MPIR   LinBox   PPL   NumPy

Languages : Cython   Python   C   Pythran

Architectures : SIMD   Multicore server   HPC cluster   Cloud
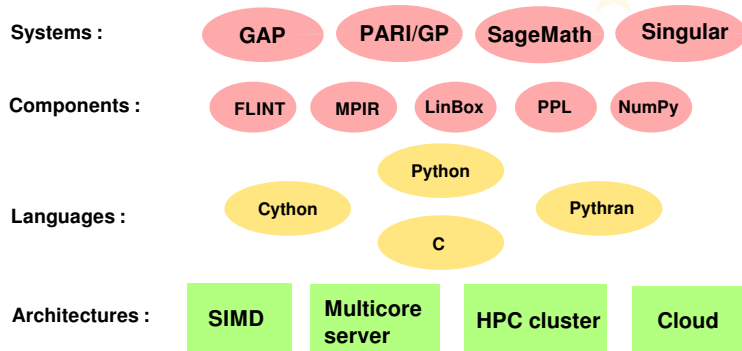
High performance mathematical computing

Goal:

- Improve/Develop parallelization of software components
- Expose them through the software stack
- Offer High Performance Computing to VRE's users

Milestone M8: Seamless use of parallel computing architecture in the VRE (proof of concept)

Astrid wants to run compute intensive routines involving both dense linear algebra and combinatorics. She has access through a JupyterHub-based VRE to a high end multi-core machine which includes a vanilla SAGE installation. She automatically benefits from the HPC features of the underlying specialized libraries (LinBox, ...). This is a proof of concept of the overall framework to integrate the HPC advances of specialized libraries into a general purpose VRE. It will prepare the final integration of a broader set of such parallel features for the end of the project

Outline

Workpackage management

Exact linear algebra
  Exact linear algebra algorithms and implementations (D5.12).
  Distributed computing

Combinatorics
  Refactor and optimize Sage's Combinatorics (D5.11)

Progress report on other tasks
  T5.1: Pari
  T5.2: GAP
  T5.4: Singular

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Outcome of WorkPackage 5

Component	Review 1	Review 2	Final review
T5.1 Pari/GP			D5.16
T5.2 GAP			D5.15
T5.3 LinBox		D5.12	D5.14
T5.4 Singular	D5.6, D5.7		D5.13
T5.5 MPIR	D5.5, D5.7		
T5.6 Combinatorics	D5.1	D5.11	
T5.7 Pythran	D5.2	D5.11	
T5.8 SunGrid Engine	D5.3		

Overall

▶ 20+ software releases

▶ 7 research papers

Addressing recommendations of review 1

Recommendation 10: *Regarding WP5,* **make contacts** *with HPC community in order to ascertain current state-of-the-art. The work in this WP needs to be* **nearer the leading edge***.*

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Recommendation 10: *Regarding WP5, **make contacts** with HPC community in order to ascertain current state-of-the-art. The work in this WP needs to be **nearer the leading edge**.*

Leading edge achievements in linear algebra

- ▶ symmetric factorization outperforms LAPACK implementation
- ▶ new non-hierarchical generator for quasiseparable matrices
- ▶ large scale parallelization of rational linear solver
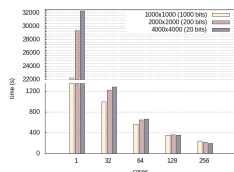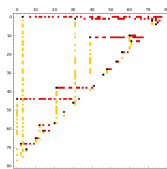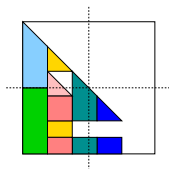
Strengthening interactions with numerical HPC community

Existing connection

Dense linear algebra numerical BLAS used for exact FFLAS for 17 years

Pointwise interactions: J. Dongarra, L. Grigori, J-Y. L'Excellent, etc

Publications to main HPC venues: SIAM-PPSC, EuroPar, PMAA, ParCo

Animation: involved in the French CNRS *Calcul* working group (Sci. Comp.)

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Recently established

- With the BLIS group:
  - Reporting bugs (SIMD vectorization)
  - Sharing experience in implementing Strassen's algorithm
- On-going collaboration with T. Mary (`Mumps`) and S. Chandrasekaran (UCSB) on quasiseparable matrix algorithmic

Outline

Task 5.3: LinBox, High performance exact linear algebra

Mathematics is the art of reducing any problem to linear algebra

– W. Stein

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Linear algebra: a key building block for HPC

Similarities with numerical HPC

- central elementary problem to which others reduce to
- (rather) simple algorithmic
- high compute/memory intensity

Task 5.3: LinBox, High performance exact linear algebra

Mathematics is the art of reducing any problem to linear algebra
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Linear algebra: a key building block for HPC

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Specificities

- Multiprecision arithmetic $\Rightarrow$ lifting from finite precision ($\mathbb{F}_p$)
- Rank deficiency $\Rightarrow$ unbalanced dynamic blocking
- Early adopter of subcubic matrix arithemtic $\Rightarrow$ recursion

D5.12: Exact linear algebra algorithms and implementations. Library maintenance and close integration in mathematical software for LinBox library

1. Algorithmic innovations:
   1.1 Rank deficient dense Gaussian elimination
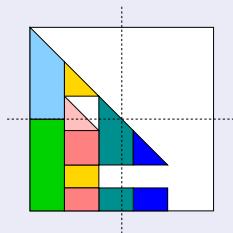   1.2 Quasiseparable matrices
   1.3 Outsourced computing security
2. Software releases and integration:
   2.1 LinBox ecosystem: LinBox, fflas-ffpack, givaro
   2.2 SageMath integration

Rank deficient dense Gaussian elimination
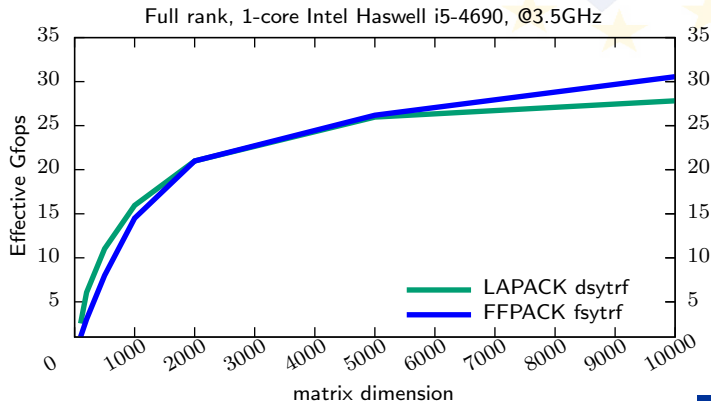
[ISSAC'18] Symmetric triangular factorization

- First unconditional recursive algorithm
- Pivoting revealing the Rank Profile Matrix
- $O(n^2 r^{\omega-2})$ ($= 1/3n^3$ with $\omega = 3, r = n$)
- Also hot topic in numerical linear algebra
  (LAPACK Working notes 294, Dec'17)

LAPACK vs FFPACK modulo $8\,388\,593$

n	LAPACK (numerical) dsytrf (LDLT)	FFPACK (exact) fsytrf (LDLT)
5000	1.60s	1.59s
10000	11.98s	10.90s

Full rank, 1-core Intel Haswell i5-4690, @3.5GHz

Quasiseparable matrices

Matrices with low off-diagonal rank

[ISSAC'16, JSC'18] New compact representation and algorithms

- Matches the best space complexities
- Reduction to matrix multiplication
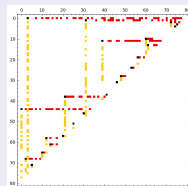- **Breakthrough:** flat representation (non hierarchical)

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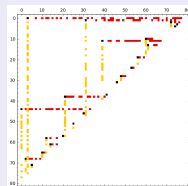- ▶ **Breakthrough:** flat representation (non hierarchical)

Follow-up: on-going collaboration with numerical HPC
experts:
- ▶ S. Chandrasekaran (UCSB)
- ▶ T. Mary (U. Manchester, `Mumps`)

Software releases and integration

LinBox ecosystem

`givaro:` field/ring arithmetic

`fflas-ffpack:` dense linear algebra over finite field

`LinBox:` exact linear algebra

Tightly integrated in `SageMath`

Software releases and integration

LinBox ecosystem

`givaro:` field/ring arithmetic   4 releases

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Tightly integrated in `SageMath`   13 tickets

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Featuring

▶ Full functional implementations of new algorithmic contributions

▶ Improved vectorization and parallel routines

▶ Drastic improvement of reliability (continuous integration, test-suite
  coverage, randomized certificates, etc)
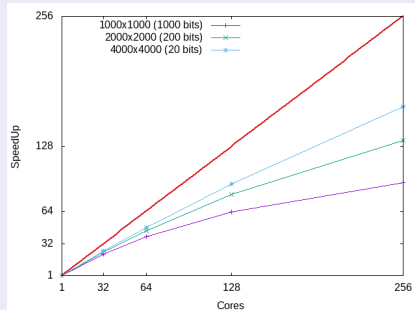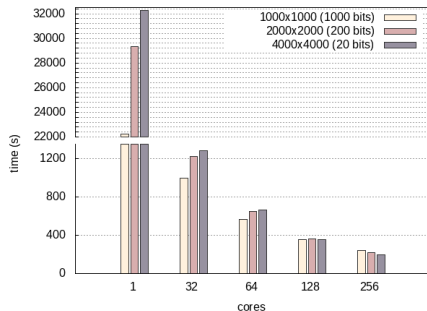
Distributed computing (on-going work)

D5.14: Distributed exact linear system solving

- 2 full time engineers
- Communication and serialization layer done
- Prototype MPI parallelization of Chinese remainder based solver.

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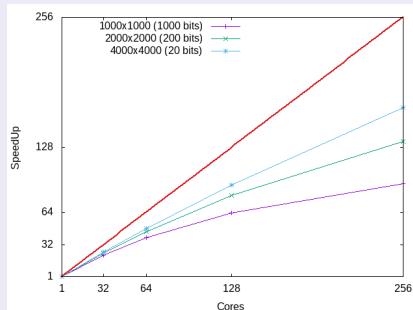- Prototype MPI parallelization of Chinese remainder based solver.

Distributed computing (on-going work)

D5.14: Distributed exact linear system solving

Roadmap:

- Major refactorization of LinBox solver code under way
- Hybrid combination of CRT+Dixon and parallelization.
- Hyrbid OpenMP-MPI implementation
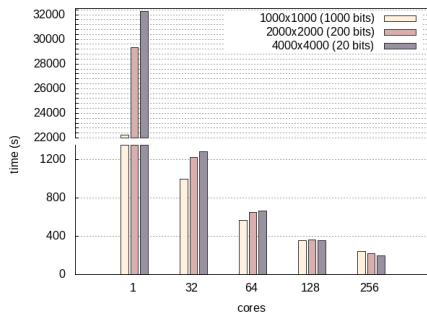
Outline

Task 5.6: HPC infrastructure for Combinatorics

Parallel algebraic computations exhibit high degrees of irregularity, at multiple levels and make no use of floating-point operations. This combination means that symbolic computations are not suited to conventional HPC paradigms.
– P. Maier, D. Livesey, H.-W. Loidl, P. Trinder

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General situation

Given a set S of combinatorial objects we want to

- find (or pick at random) an element of S
- list (or count) the elements of S

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Specificities of combinatorics

- **huge**: S does not fit in memory
- **embarassingly parallel**: $S = S_1 \cup \ldots \cup S_k$
- **unbalanced**: S_i sizes are highly unbalanced

D5.11: Refactor and optimise the existing combinatorics Sage code using the new developed Pythran and Cython features.

Algorithmic innovations and software integration through examples:

1. Example 1: polytopes
2. Example 2: numerical semigroups

Example 1: polytopes (description)

Example

Some combinatorial objects can be encoded as integer vectors in polytopes.
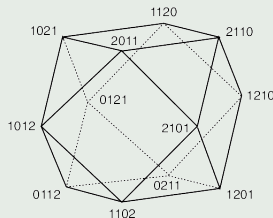
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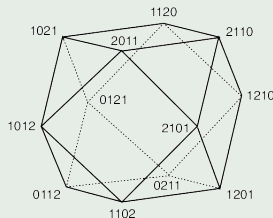
- Efficient algorithms available (*e.g.* Double Description, Barvinok)
- High performance libraries (*e.g.* PPL, `Normaliz`, `Polymake`)
- Useful for many combinatorial problems

Example 1: polytopes (ODK work)

ODK outcomes

`pplpy library:` Python interface to the high performance PPL (rational polytopes)

`e-antic library:` C/C++ library for exact computation over number fields. Building block for `Normaliz`.

Workshop: Sage Days 84

`SageMath:` improvement of native code and libraries interfaces

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ODK outcomes

`pplpy` library: Python interface to the high performance PPL (rational polytopes)   6 releases

`e-antic` library: C/C++ library for exact computation over number fields. Building block for `Normaliz`.   release soon

Workshop: Sage Days 84

`SageMath`: improvement of native code and libraries interfaces   10 tickets

Example 2: semigroups (description)

Example

Numerical semigroup are certain subsets of non-negative integers.

$$\langle 1 \rangle$$
$$|$$
$$\langle 2, 3 \rangle$$

$\langle 2, 5 \rangle$ $\langle 3, 4, 5 \rangle$

$\langle 2, 7 \rangle$ $\langle 3, 4 \rangle$ $\langle 3, 5, 7 \rangle$ $\langle 4, 5, 6, 7 \rangle$

$\vdots$ $\vdots$ $\vdots$ $\vdots$

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$$\vdots \qquad\quad \vdots \qquad\quad \vdots \qquad\quad \vdots$$
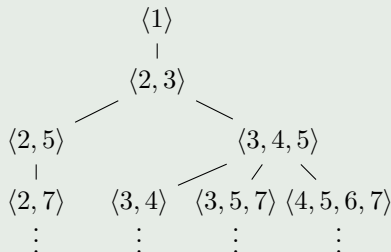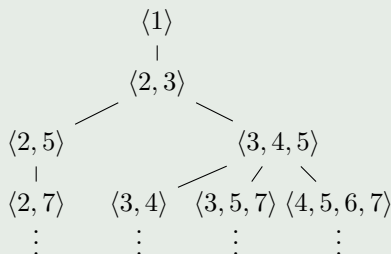
▶ Many mathematical questions still open
▶ Highly unbalanced tree

Example 2: semigroups (ODK work)

A SageMath implementation of work-stealing map-reduce

▶ Work stealing algorithm (Leiserson-Blumofe)
▶ Easy to use, easy to call from SageMath with many use cases
▶ Scale well with the number of cores and reasonably efficient

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A typical speedup (binary sequences)

# processors	1	2	4	8
Speedup	$\times 1$	$\times 1.55$	$\times 2.43$	$\times 2.87$

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integrated in SageMath

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- innovative SIMD code for combinatorics
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Operation	Speedup
Sum of a vector of bytes	$\times 3.81$
Sorting a vector of bytes	$\times 21.3$
Inverting a permutation	$\times 1.97$
Number of cycles of a permutation	$\times 41.5$
Number of inversions of a permutation	$\times 9.39$
Cycle type of a permutation	$\times 8.94$

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Open-source library

Outline

T5.1: Pari

D5.16: Pari Suite release, fully supporting parallelization

- D5.10 (merged in D5.16):
  Generic parallelization engine is now mature (released since Nov 2016).
  Support POSIX-threads and MPI.
- Current work: applying it throughout the library
  - Chinese remaindering
  - Rational linear algebra
  - Discrete logarithm
  - Resultants
  - APRCL primality testing

T5.2: GAP

D5.15: Final report of GAP development

- 8 releases were produced integrating contributions of D3.11 and D5.15
- Towards an integration of HPC-GAP: main release GAP-4.9
  - Build system refactoring
  - Ability to compile in HPC-GAP compatibility mode
- Work in progress:
  - Multithreaded linear algebra: at the level of the `Meataxe` library
  - Introspection functionalities: on-the-fly optimisation decision

T5.4 Singular

D5.13: Parallel sparse polynomial multiplication

FLINT now supports fast sparse multivariate polynomials:

- addition, subtraction, multiplication,
- division, division with remainder, GCD
- evaluation, partial evaluation, composition

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Parallelization of the (sparse) multiplication

#	$\mathbb{Z}$	$\mathbb{Z}_{2^{64}-1}$
1	34145(1.0x)	30349(1.0x)
2	14856(2.3x)	12641(2.4x)
3	10844(3.1x)	8294(3.6x)
4	7205(4.7x)	6274(4.8x)
5	7621(4.4x)	5315(5.7x)
6	6156(5.5x)	4152(7.3x)
7	5679(6.0x)	3739(8.1x)
8	4458(7.6x)	3047(9.9x)

T5.4 Singular

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7	5679(6.0x)	3739(8.1x)
8	4458(7.6x)	3047(9.9x)

- Planned improvements to the memory manager $\Rightarrow$ closer to linear scaling
- Parallel division and GCD implementations are in progress.
- Integration into Factory/Singular remains to be done

Conclusion

Outcome of WorkPackage 5

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Overall

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- 7 research papers

Lessons learnt

From dedicated to general purpose HPC components:

- ▶ Early instances of HPC computer algebra: dedicated to some target application (breaking RSA, etc)
- ▶ Building a general purpose HPC component:
  - ▶ challenging
  - ▶ longer term sustainability

Risk of technology dependency

- ▶ Cilk: from success to shut-down
- ▶ Interchangeability and modularity

Extra Slides

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Outsourced computing security (D5.12)

Exploratory aspect: Computation over the Cloud

Outsourcing computation on the cloud:

- ▶ trusted lightweight client computer
- ▶ untrusted powerful cloud server
- ⇒ need for certification protocols

Multiparty computation:

- ▶ each player contribute with a share of the input
- ▶ shares must remain private

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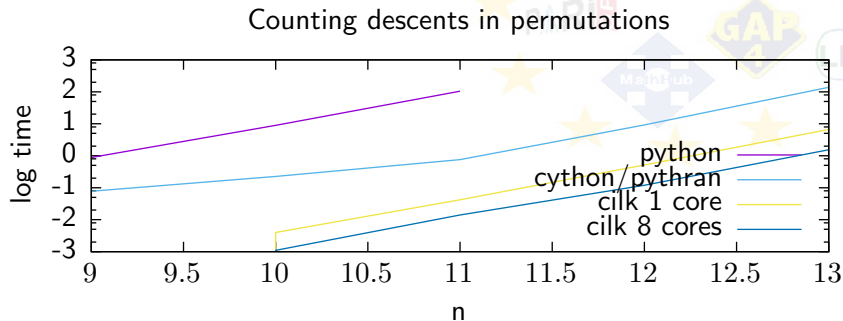- ▶ shares must remain private

Contribution

ISSAC'17: Linear time certificates for LU, Det., Rank Profile matrix, etc

In submission: Secure multiparty Strassen's algorithm

Exploration: Python, Cython, Pythran and Cilk (D5.8)

workshop: Interfacing (math) software with low level libraries

Counting descents in permutations

- ▶ Python (interpreted language) slow.
- ▶ Cython/Pythran (Python to C compilers) efficient.
- ▶ Cilk (SIMD and multithread parallelism) very promising.