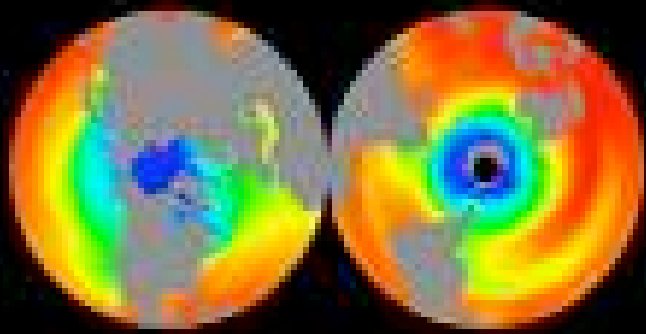
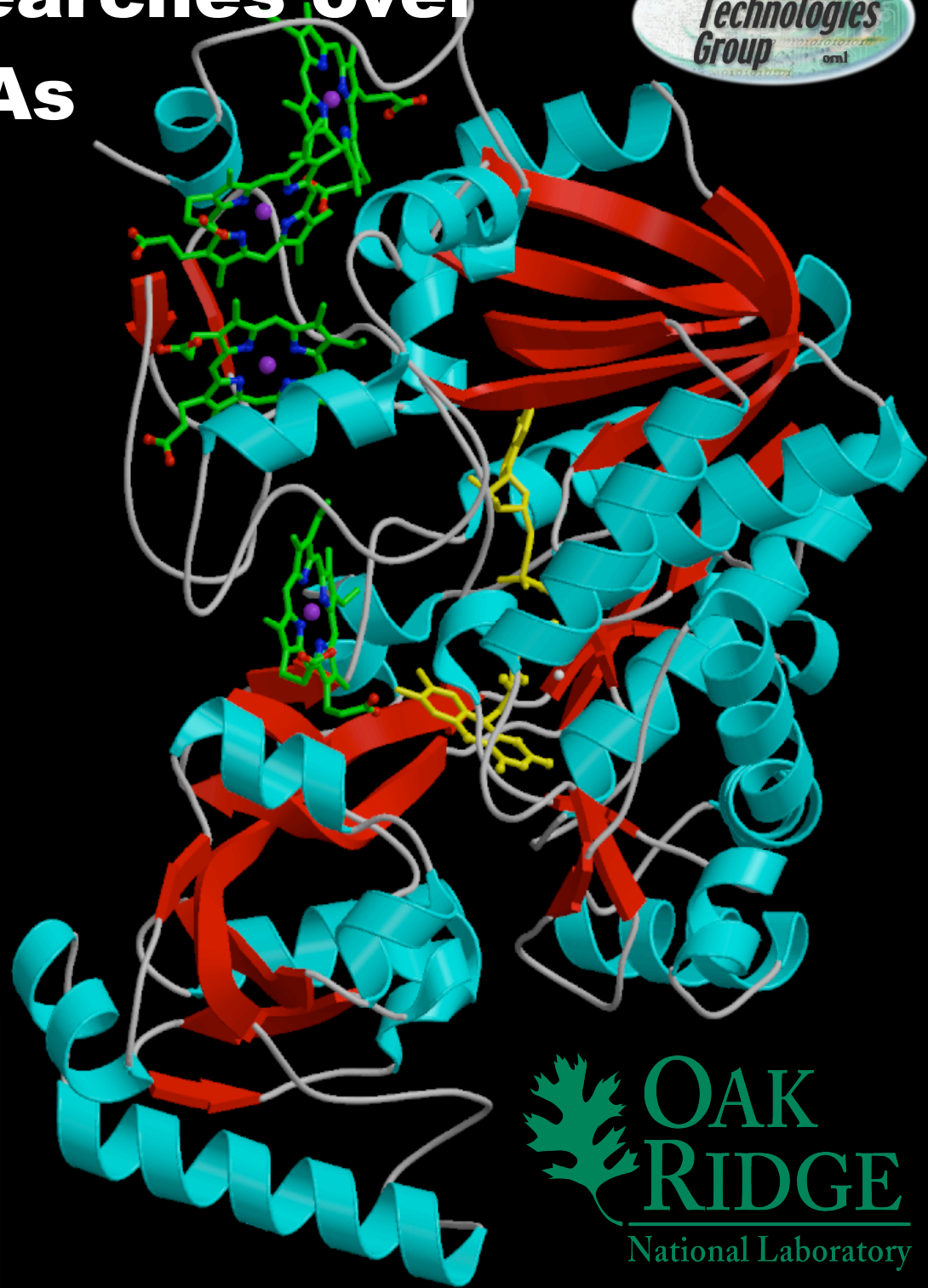
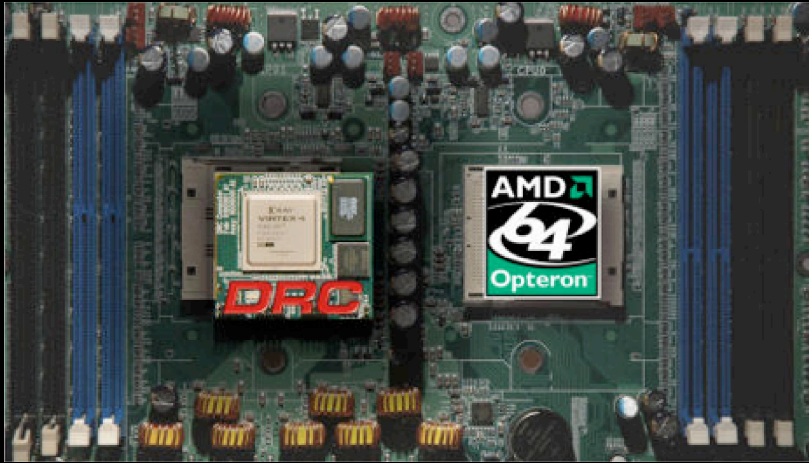


Speeding Genome Searches over 1000X with 150 FPGAs



Olaf O. Storaasli

Google Olaf ORNL

Cray Users Group '08 Helsinki



Explore FPGAs for future ORNL HPC



HPC vendors adopting FPGAs

sgi

CRAY®
THE SUPERCOMPUTER COMPANY

Steve Scott, CTO HPCWire 24/3/0606

*“After exhaustive analysis, Cray concluded that, although multi-core commodity processors will deliver some improvement, exploiting parallelism through a variety of processor technologies using scalar, vector, multithreading and **hardware accelerators***

*(e.g., **FPGAs** or ClearSpeed co-processors) creates the **greatest opportunity** for application acceleration.” => **Cray XT5h***

+ **HP, SRC, Nallatech, DRC,** 

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Contents

- Background: Why FPGAs?
- ORNL success: FPGA systems, tools and up to 100x speedup

• Partners:  XILINX® Research Lab, , SRC



Future Supercomputer Technologies



*Future
Technologies
Group* oml

The logo for Future Technologies Group features the text "Future Technologies Group" in a stylized, italicized font. The word "Future" is on the top line, "Technologies" is on the middle line, and "Group" is on the bottom line. To the right of "Group" is the acronym "oml". The text is set against a background of a green and blue oval shape with a circuit-like pattern.

**OAK
RIDGE**
National Laboratory

The logo for Oak Ridge National Laboratory features a green oak leaf icon to the left of the text "OAK RIDGE" in a bold, serif font. Below "OAK RIDGE" is the text "National Laboratory" in a smaller, sans-serif font. The entire logo is set against a white background.

Future Supercomputer Technologies

Commodity: 2^n multi \Rightarrow many core

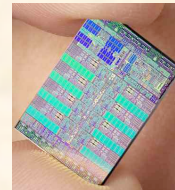
Special: *El Dorado, Cyclops, PiM*

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Accelerators



ClearSpeed™

Future
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Group
oml


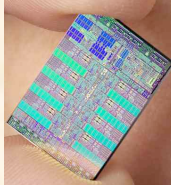

OAK
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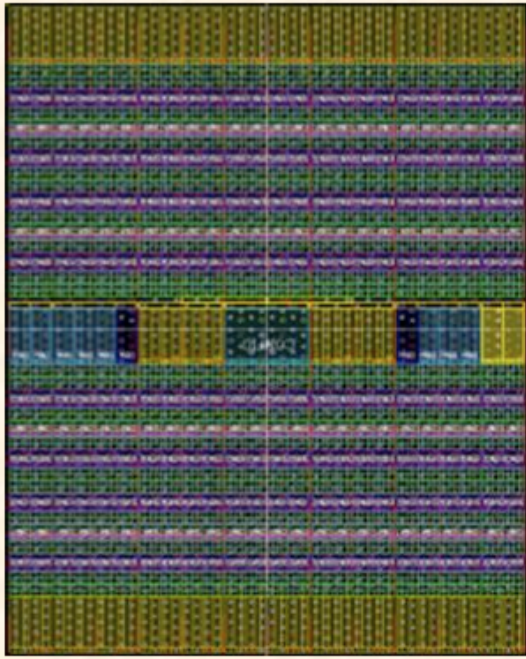
- **FPGA:** DSP \Rightarrow HPEC \Rightarrow HPC 
- **Cell:** IBM, Sony, Toshiba 
- **GPUs:** on μ P?
- **Array:** 



What's an FPGA? Your "custom chip"

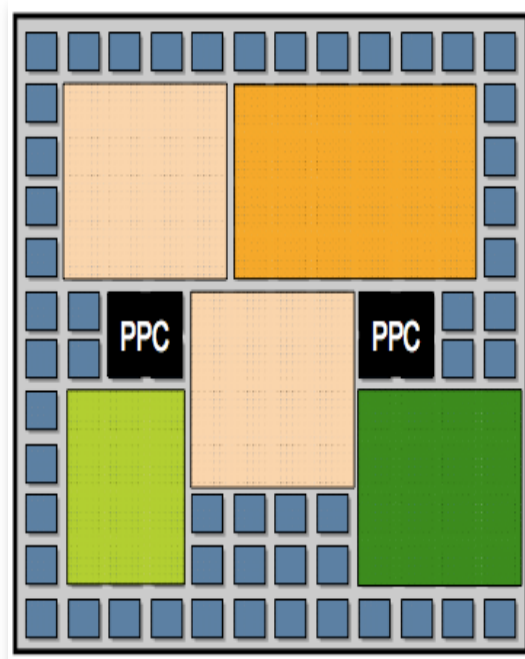
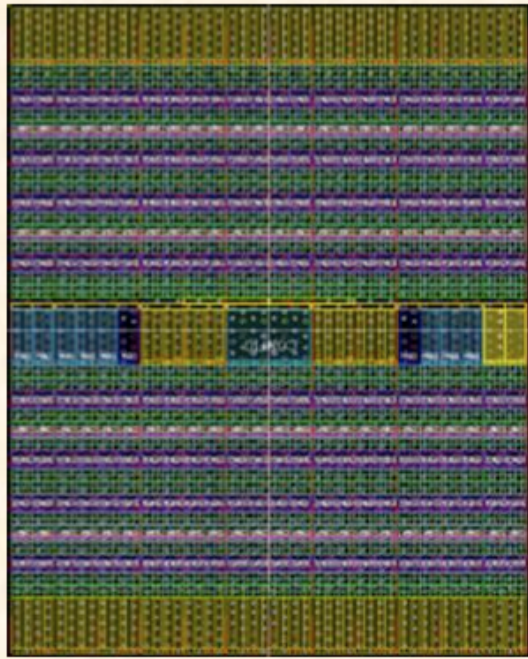


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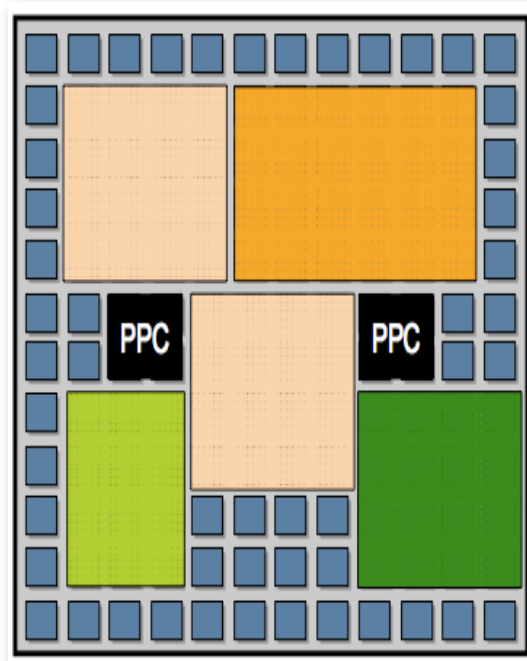
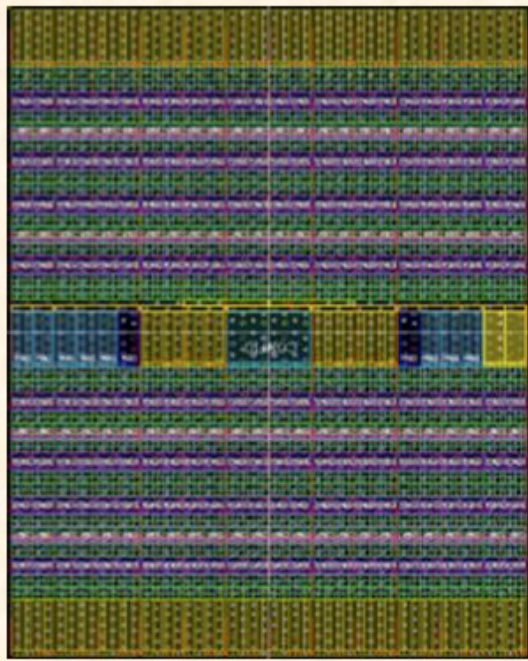
Xilinx Virtex4 FPGA:

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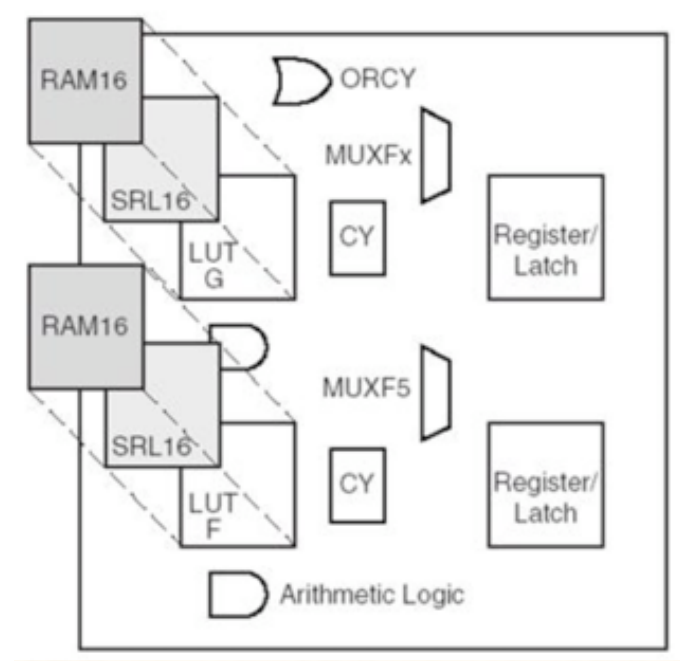


Xilinx Virtex4 FPGA: 89K slices (miniCPUs)

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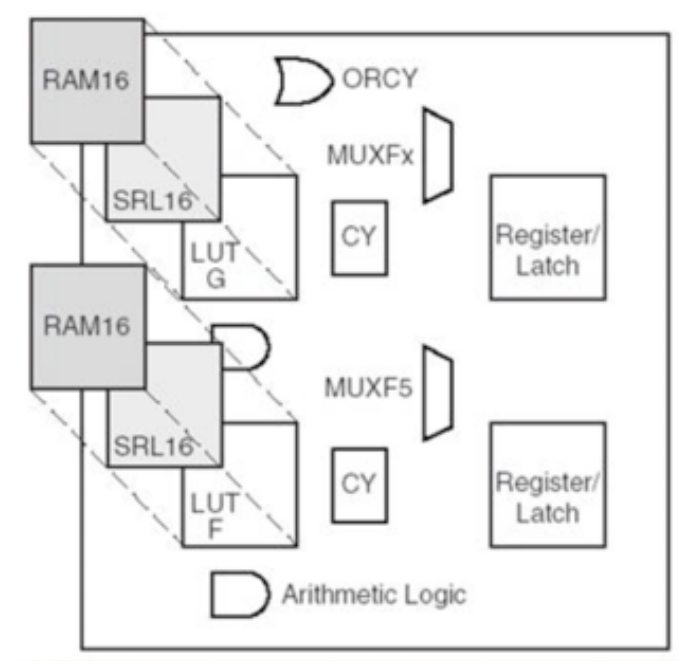
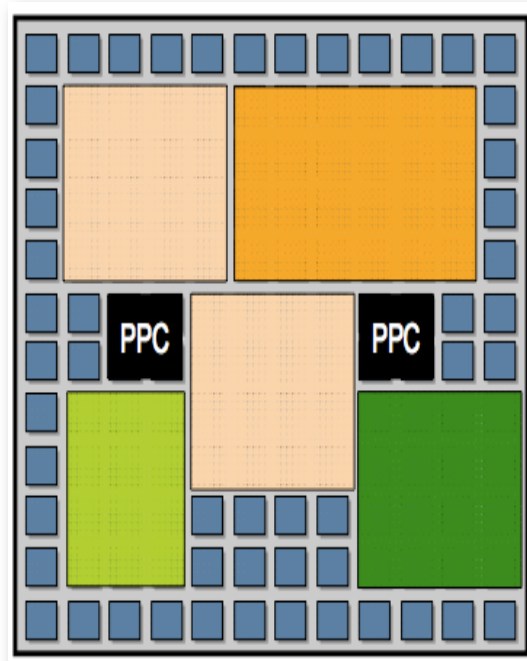
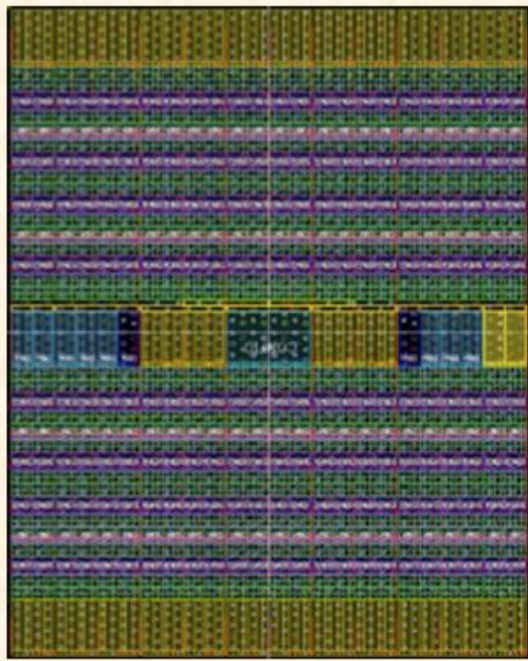


Xilinx Virtex4 FPGA: 89K slices (miniCPUs)



FPGA Logic slice

What's an FPGA? Your "custom chip"



Xilinx Virtex4 FPGA: 89K slices (miniCPUs)

FPGA Logic slice

- Logic array: user-tailored to application
- On-chip RAM, multipliers & PowerPCs
- Gigabit transceivers/DSP blocks => FastIO/precision
- 100–1000 operations/clock cycle

Why FPGAs?



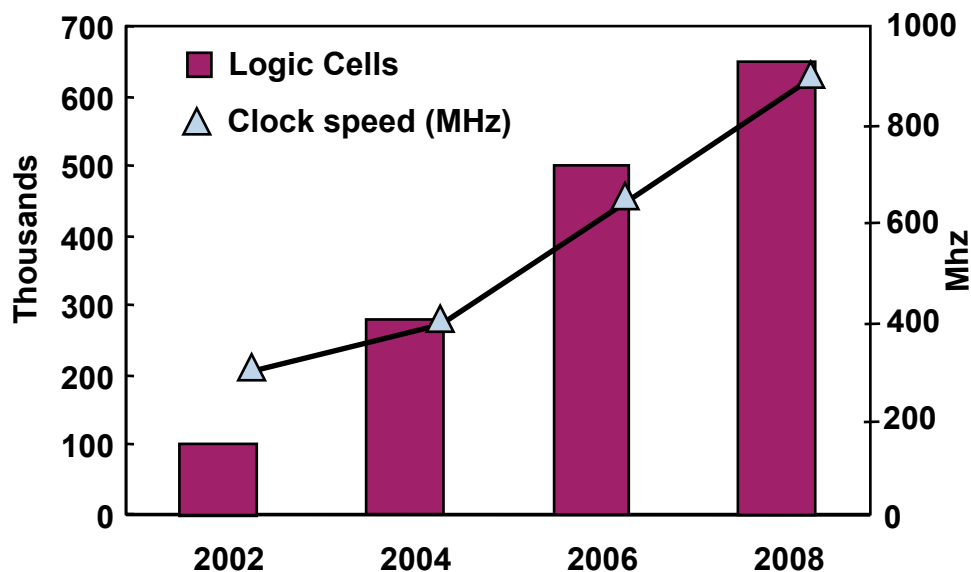
Why FPGAs?



- **Performance:** optimal silicon use (maximize parallel ops/cycle)
- **Rapid growth:** Cells, Speed, I/O
- **Power:** 1/10th CPUs
- **Flexible:** *tailor* to application
- **Advances:** Telecom industry spinoff

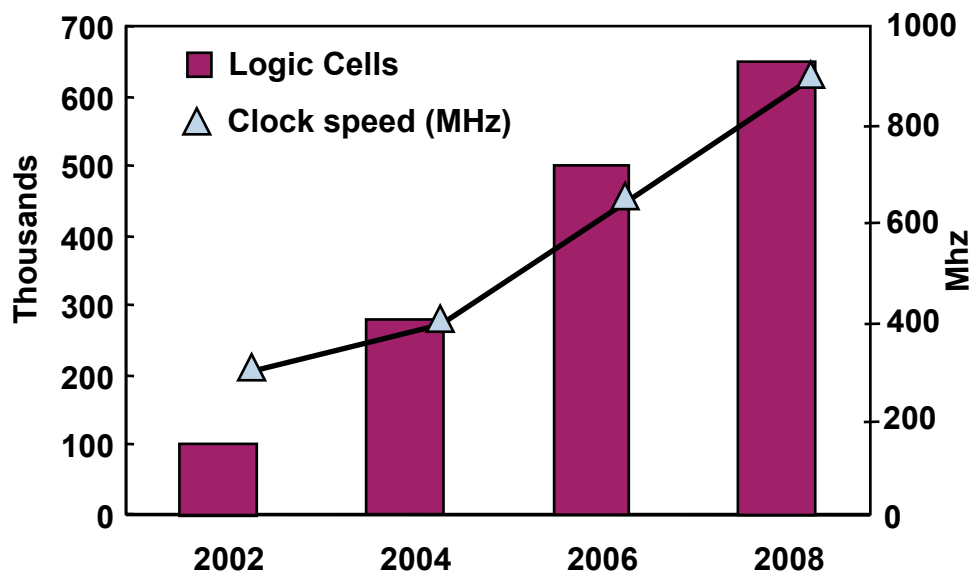
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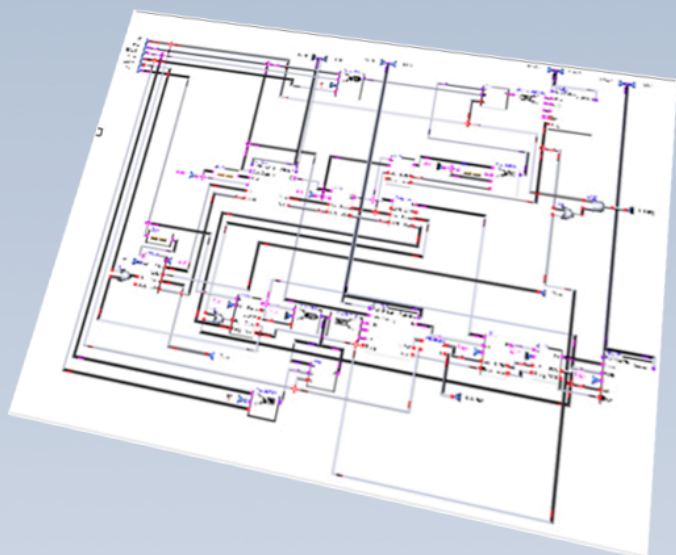


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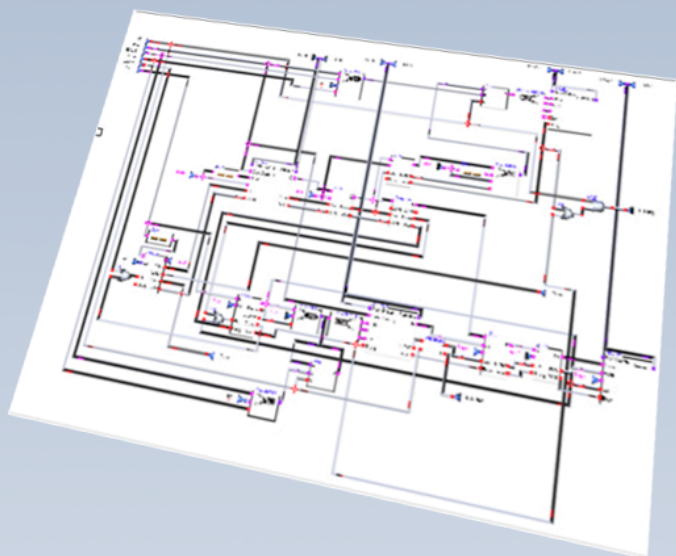
Exploring programming options



Viva: Graphical Icons—3-dimensional

Exploring programming options

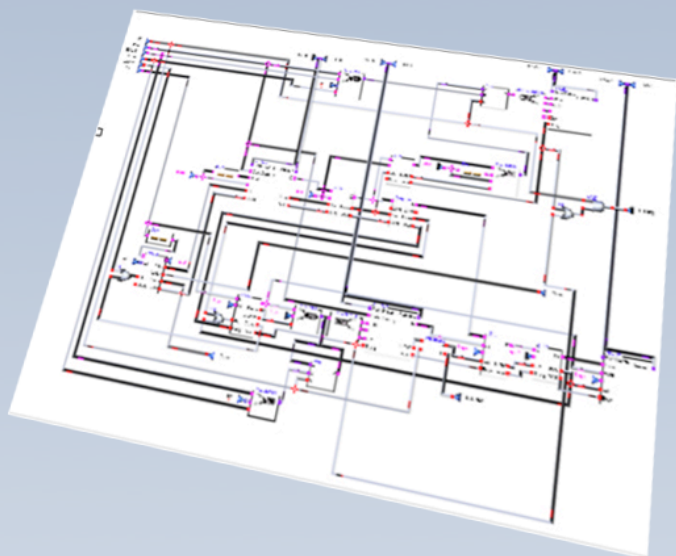
Gauss matrix solver



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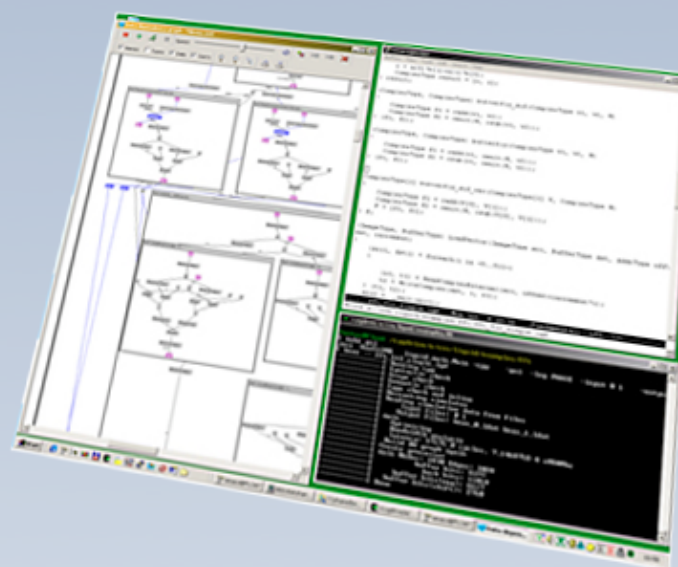
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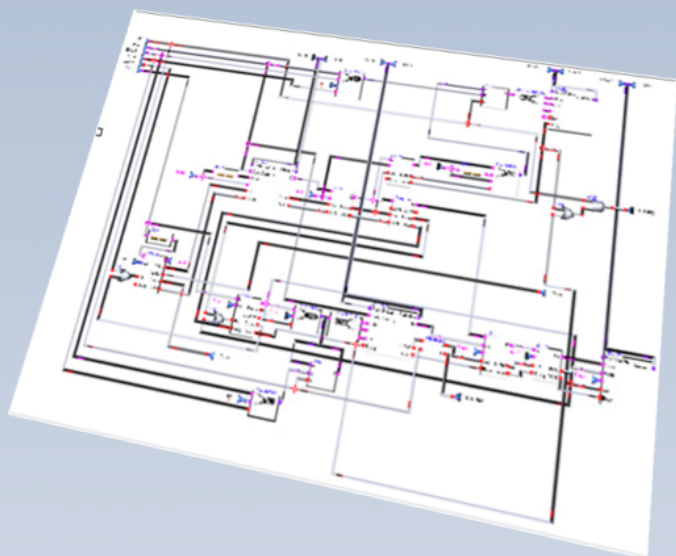
Compiler, simulator, and debugger



MitrionC: Text/flow—1-dimensional

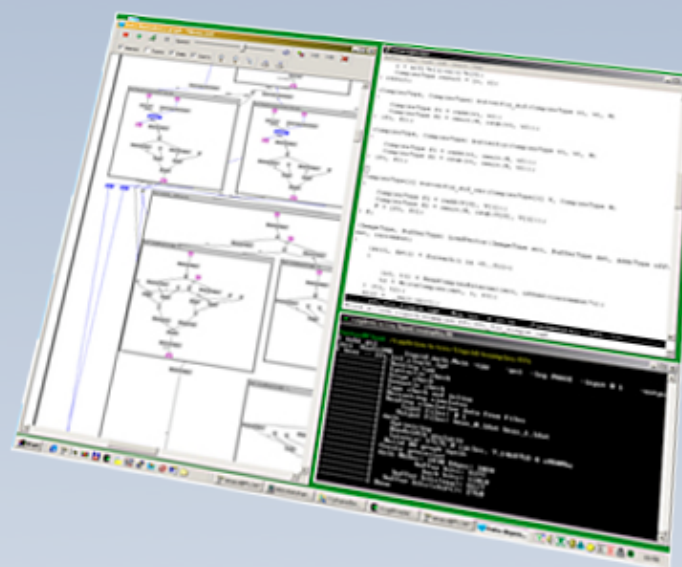
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MitrionC: Text/flow—1-dimensional

+ Carte/SRC, CHiMPS-VHDL/Xilinx ,  DSPlogic

Applications



Applications

- **Genomics**
- **Matrix Equation Solution**
- **Molecular Dynamics, Weather/Climate**



Openfpga.org Smith-Waterman Benchmark

- **FASTA** (University of Virginia) application
<http://fasta.bioch.virginia.edu>
- Uses **search34** code & Cray **SWA** core
- Human Genome Data: 4GB compressed
3685 searches (MPI on ORNL Cray XD1)



Alignment of ACGAACCCTTGC and ACGTATGC

	0	A	C	G	T	A	T	G	C
0	0	0	0	0	0	0	0	0	0
A	0	2	0	0	0	2	0	0	0
C	0	0	4	2	1	0	1	0	2
G	0	0	2	6	4	3	2	3	1
A	0	2	1	4	5	6	4	3	2
A	0	2	1	3	3	7	5	4	3
C	0	2	4	2	2	5	6	4	6
C	0	0	2	3	1	4	4	5	6
C	0	0	2	1	2	3	3	3	7
T	0	0	0	1	3	2	5	3	5
T	0	0	0	0	3	2	4	4	4
G	0	0	0	2	1	2	2	6	4
C	0	0	2	0	1	0	1	4	8

Final alignment

A	C	G	A	A	C	C	T	T	G	C
A	C	G	T	A	-	-	-	T	G	C

Smith-Waterman Algorithm Scoring

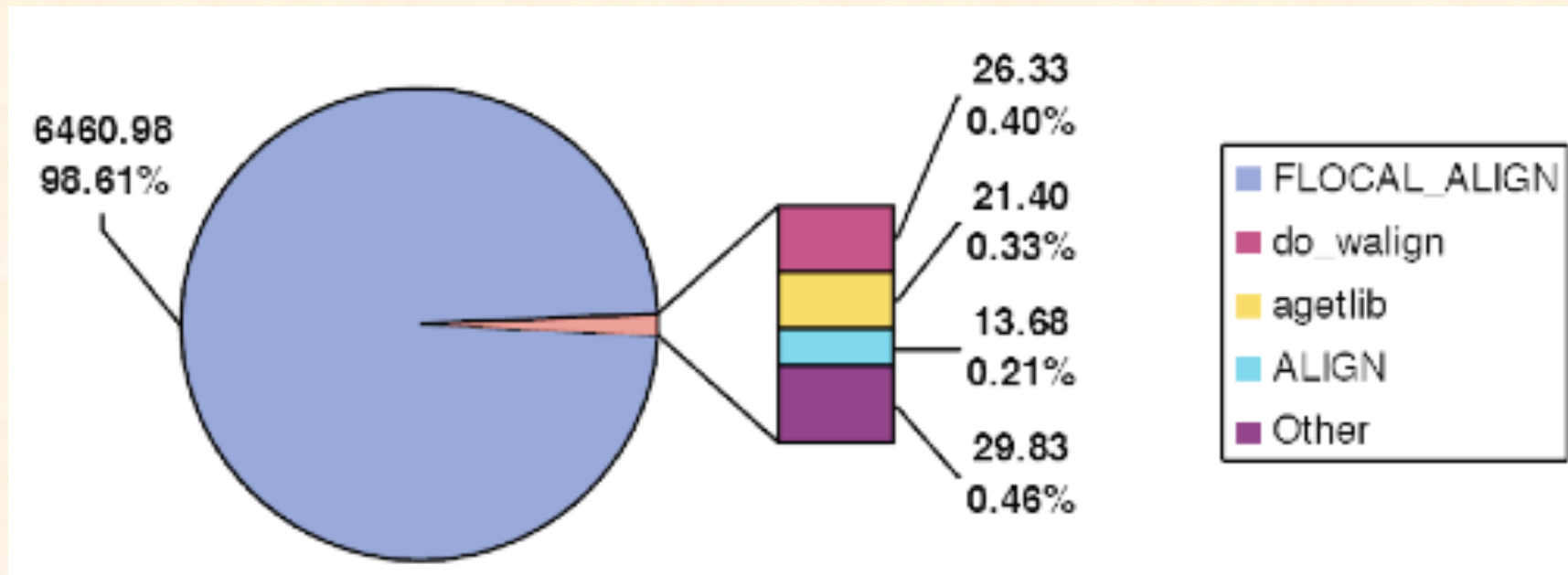
Query Sequence

Database
Sequence

	0	A	C	G	T	...	C
0	0	0	0	0	0	0	0
A	0	2	0	0	0	2	0
C	0	0	4	2	1	0	2
G	0	0	2	6			
A	0						
A	0						
C	0						
...	0						
G	0						

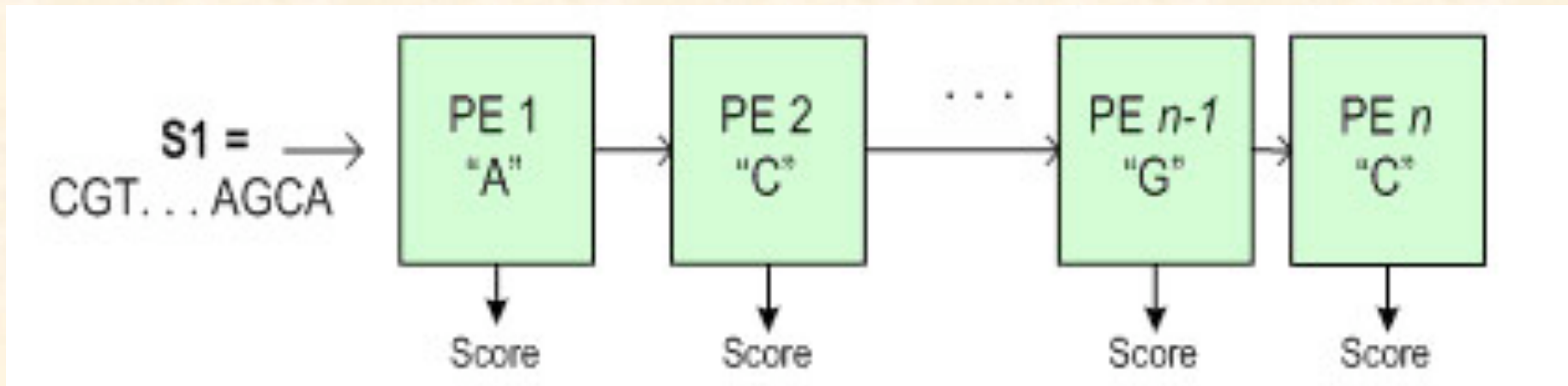
1. Initialize row & column 1 to 0
2. Score matches from upper left
3. Add to above-left score ($2+4=6$)

Search34 Computation Profile



98.61% is FLOCAL_ALIGN => VHDL kernel

Smith-Waterman Pipeline



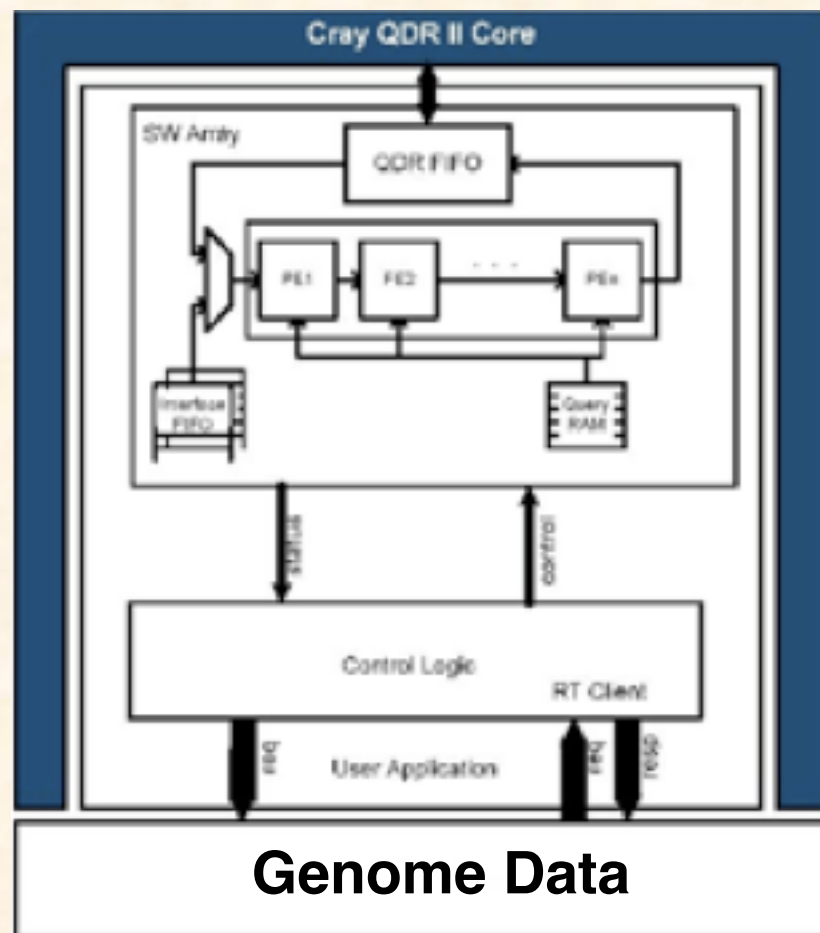
1. Query character preloaded into each PE
2. String $S1$ shifted thru pipe to compare
3. Score generated

Smith-Waterman

Parallel Score Calculation

		Query Sequence						
		0	A	C	G	T	...	C
Database Sequence	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0
	G	0	0	0	0	0	0	0
	T	0	0	0	0	0	0	PE N
	⋮	0	0	0	0	0	PE	↓
	T	0	0	0	0	PE 4	↓	
	A	0	0	0	PE 3	↓		
	A	0	0	PE 2	↓			
	G	0	PE 1	↓				
	C	0	↓					
A	0							

Overall Algorithm





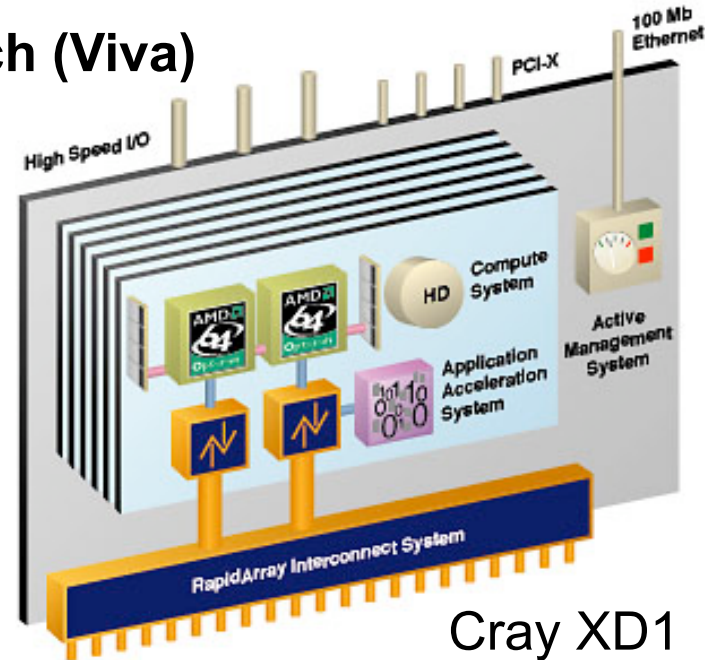
IBM Cell BladeCenter
1000 Series
1000 Series
1000 Series

IBM Cell BladeCenter
1000 Series
1000 Series
1000 Series

IBM Cell BladeCenter
1000 Series
1000 Series
1000 Series
1000 Series
1000 Series
1000 Series

ORNL FPGA hardware/tools

- SRC-6 (Carte), Digilent (Viva, VHDL), Nallatech (Viva)
- Cray XD1 (MitrionC, VHDL):
6 FPGAs + 144 Opterons
- SGI RASC-Altix/Virtex4s (MitrionC)
- CHiMPS (Bee2 => Cray XD1 => DRC => XT4)
(Xilinx early access)



Cray XD1



FPGA Performance

ORNL XD1 (Virtex2): Initial Results

Case 1: *Micro-RNA*



Storaasli - MRSC08



FPGA Performance

ORNL XD1 (Virtex2): Initial Results

Case 1: *Micro-RNA*

FPGA vs Opteron Time (hrs) for FASTA

	1	2	3	4	5
CPU 2.2GHz	75	-	-	-	-
FPGA(s) 0.2GHz	7.39	3.75	2.48	1.91	1.56
FPGA Speedup vs 1 CPU	10.15	20.0	30.2	39.3	48.1

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Output Options (Impact Speedup)

Detailed: -Q -H -f -l0 -g -3 -d 10 -b 10 -s OpenFPGA.mat -E 0.0001

Minimal: -Q -H -f -l0 -g -3 -d 0 -b 10 -s OpenFPGA.mat -E 0.0001

Cray XD1 FPGA Speedup vs. 2.2 GHz Opteron

Case 2: *Bacillus anthracis* DNA comparison

8k

16k

8k

16k



Cray XD1 FPGA Speedup vs. 2.2 GHz Opteron

Case 2: *Bacillus anthracis* DNA comparison

Virtex2 Pro 50 Speedup

	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Avg	SD
8k	26	30	27	32	30	30	29	30	30	27	31	29	31	30	31	31	31	30	29.6	1.2
16k	22	25	26	31	30	30	28	31	28	27	30	29	29	29	32	31	32	29	28.7	2.5
8k	49	49	49	50	49	49	50	49	49	49	49	49	49	49	50	49	49	49	49.4	0.2
16k	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	49	50	50	49.9	0.3



24 => Sequence AE017024

Storaasli - MRSC08



Cray XD1 FPGA Speedup vs. 2.2 GHz Opteron

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Virtex2 Pro 50 Speedup

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8k	26	30	27	32	30	30	29	30	30	27	31	29	31	30	31	31	31	30	29.6	1.2
16k	22	25	26	31	30	30	28	31	28	27	30	29	29	29	32	31	32	29	28.7	2.5
8k	49	49	49	50	49	49	50	49	49	49	49	49	49	49	50	49	49	49	49.4	0.2
16k	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	49	50	50	49.9	0.3

Virtex4 LX160 Speedup: 8 hrs => 5 mins*

	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Avg	SD
8k	36	43	39	47	44	45	43	45	45	39	46	42	46	44	46	46	46	43	43.5	2.9
16k	29	33	37	45	44	43	39	47	41	37	46	41	43	41	47	46	48	43	41.5	4.9
8k	98	98	98	97	97	98	98	98	98	97	98	98	98	98	98	98	98	97	97.6	0.1
16k	100	101	101	100	100	100	101	101	101	101	101	101	101	101	100	100	101	100	100.7	0.4

*28,873 => 288 secs

24 => Sequence AE017024



XD1 Virtex2 Speedup vs. 2.2 GHz Opteron

Case 2: *Bacillus anthracis* DNA comparison

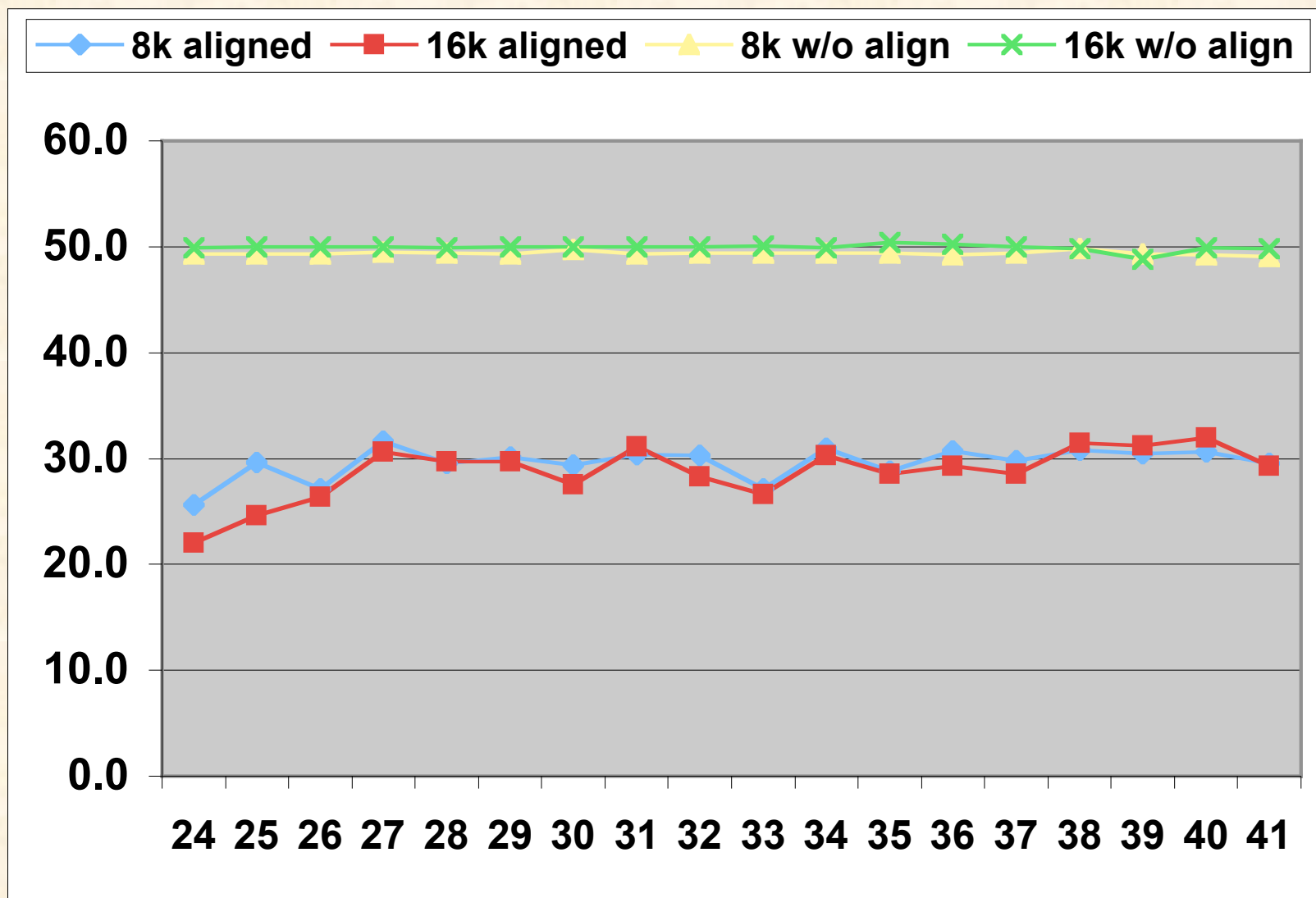


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XD1 Virtex2 Speedup vs. 2.2 GHz Opteron

Case 2: *Bacillus anthracis* DNA comparison



Genome Sequence



100x* DNA Sequence Speedup

Bacillus anthracis Human DNA comparison



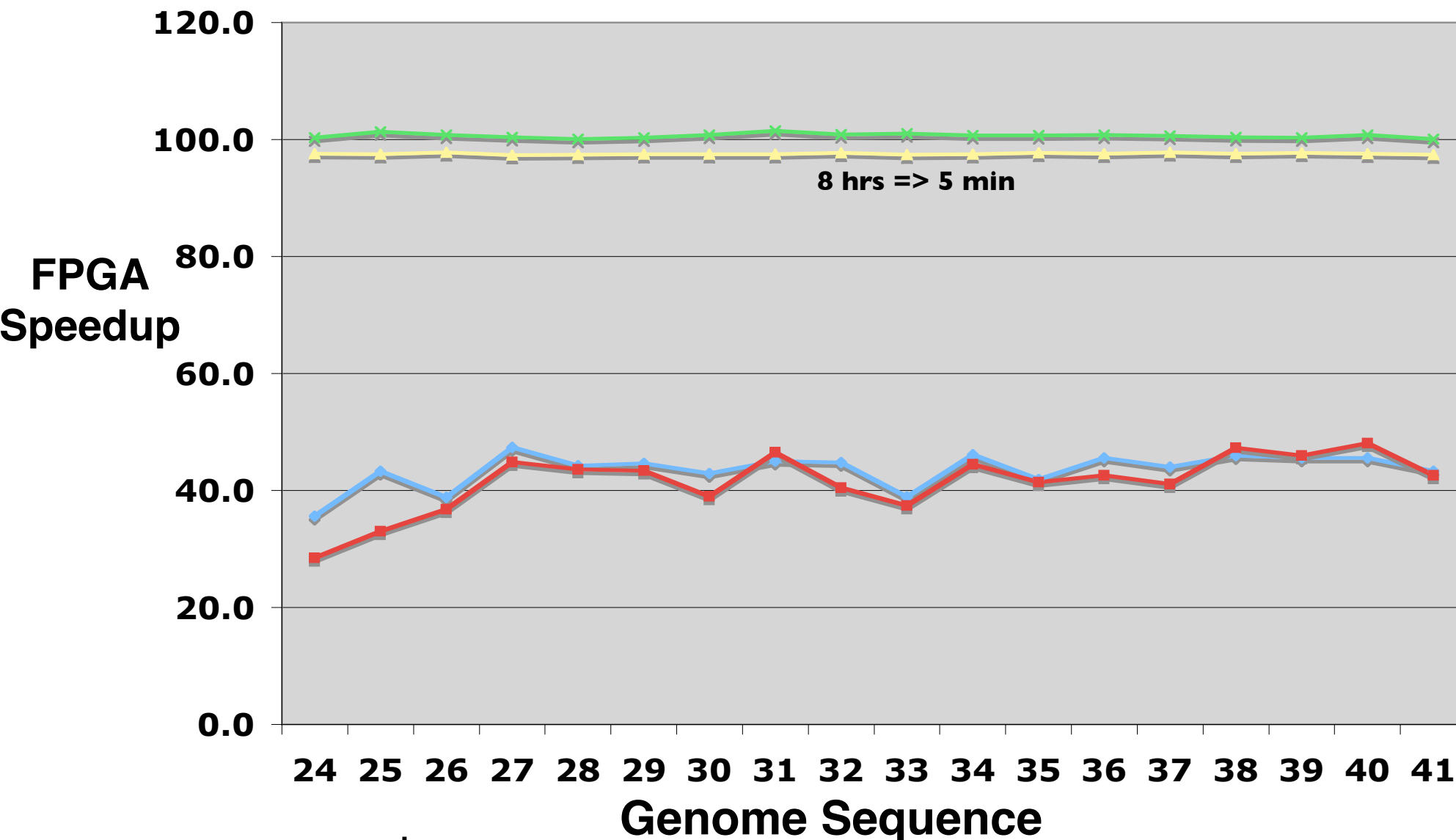
*Virtex-4 FPGA vs 2.2 GHz Opteron on Cray XD1

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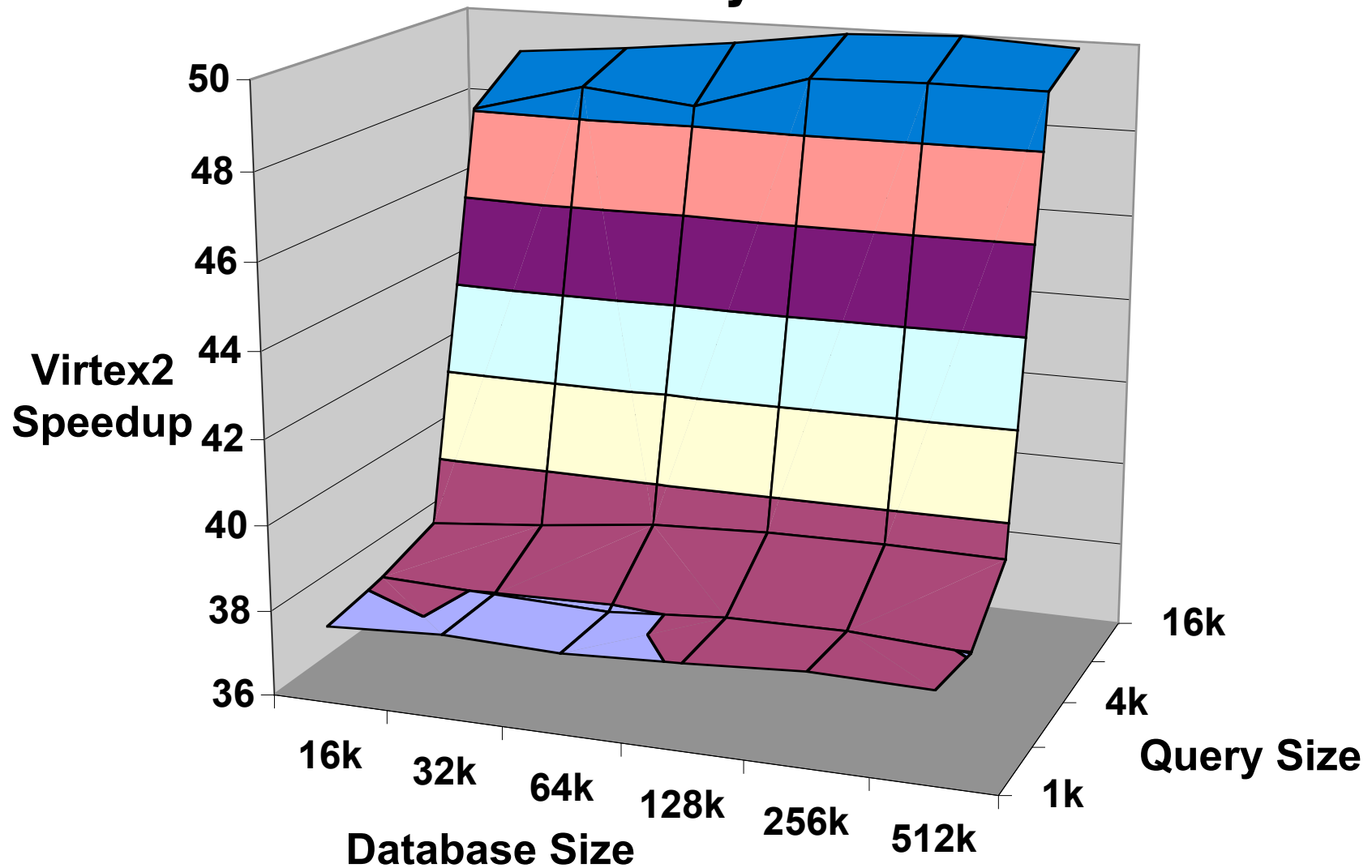


8k w/align 16k w/align 8k w/o align 16k w/o align



*Virtex-4 FPGA vs 2.2 GHz Opteron on Cray XD1

FPGA Speedup Grows with Query Size



Preliminary Results: 150 FPGAs*



*Thanks to NRL for use of 150 FPGA Cray XD1

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Solve large DNA sequencing problem:
12.5 years (150 mos.) for 1 Opteron



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Storaasli - MRSC08



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1 day for 150 FPGAs

7,350X Speedup over one 2.2 GHz Opteron

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**Next: Test performance on *64 Virtex4 FPGA Maxwell*
at Edinburgh University**

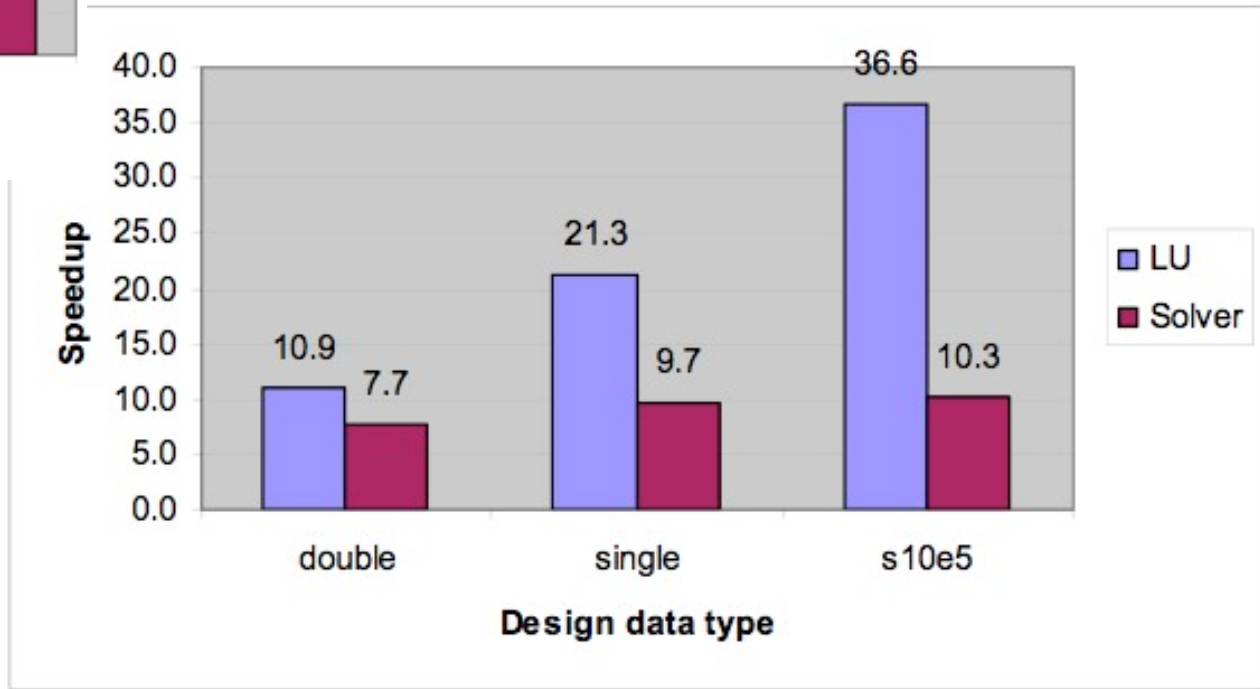
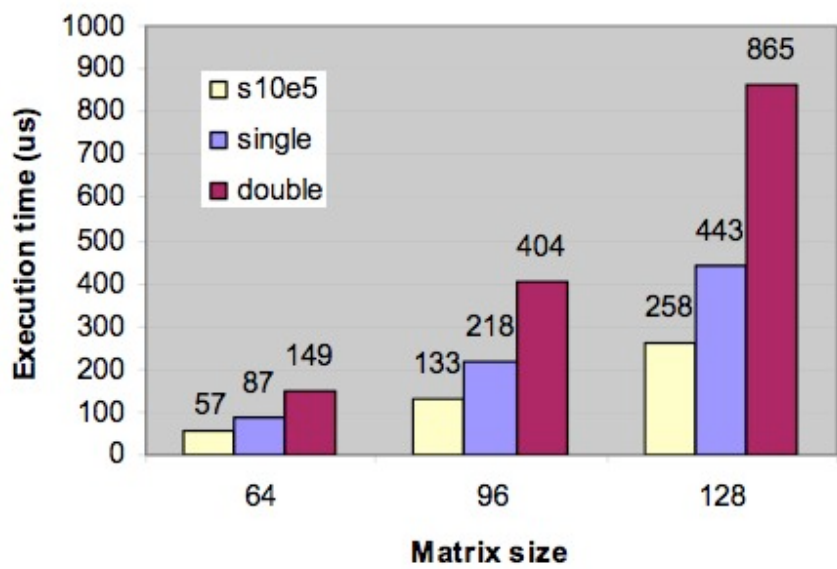


*Thanks to NRL for use of 150 FPGA Cray XD1

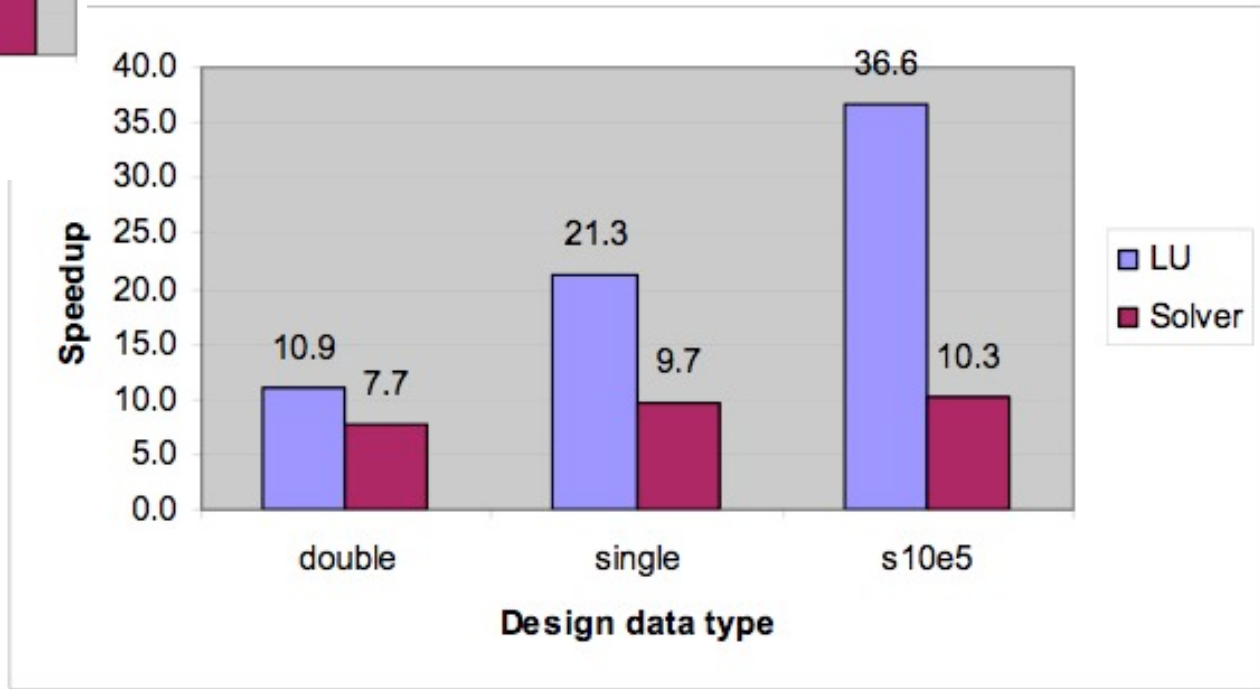
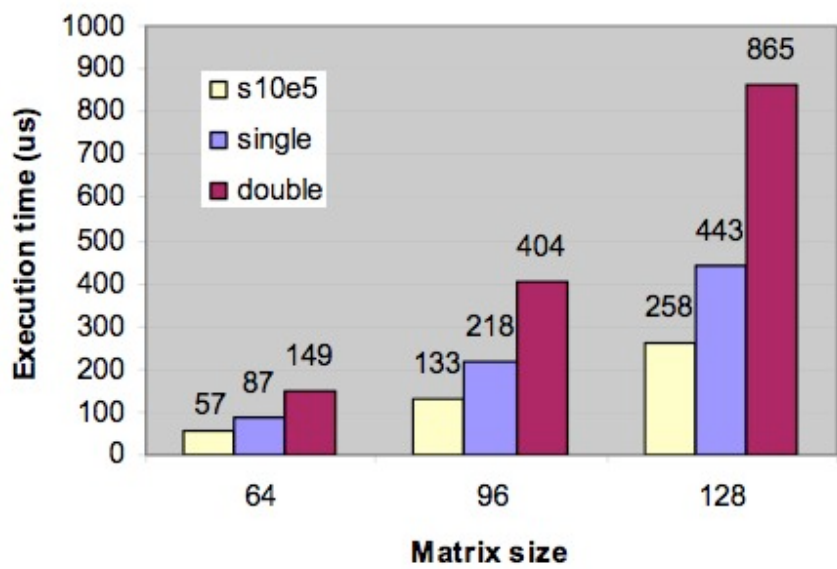
Storaasli - MRSC08



37x* LU Decomposition FPGA Speedup 10x for Matrix Equation Solver



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*Virtex-II vs 2.2 GHz Opteron

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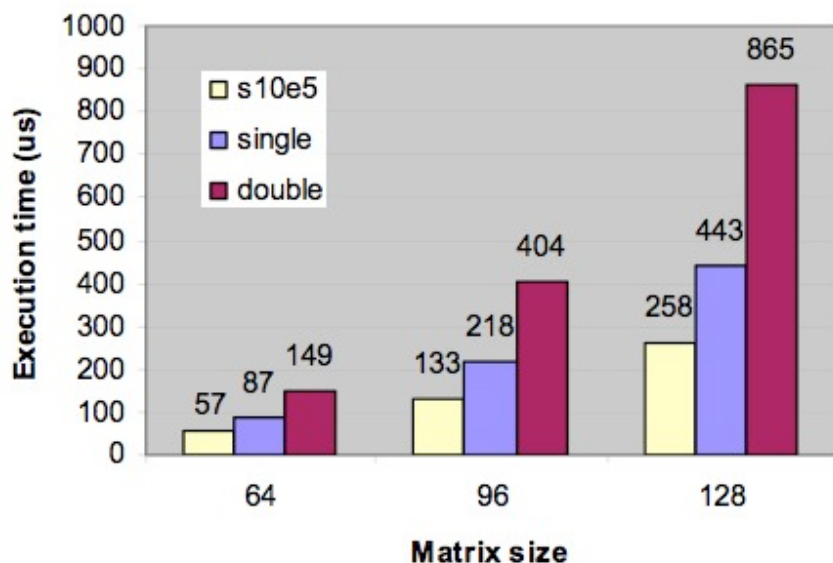
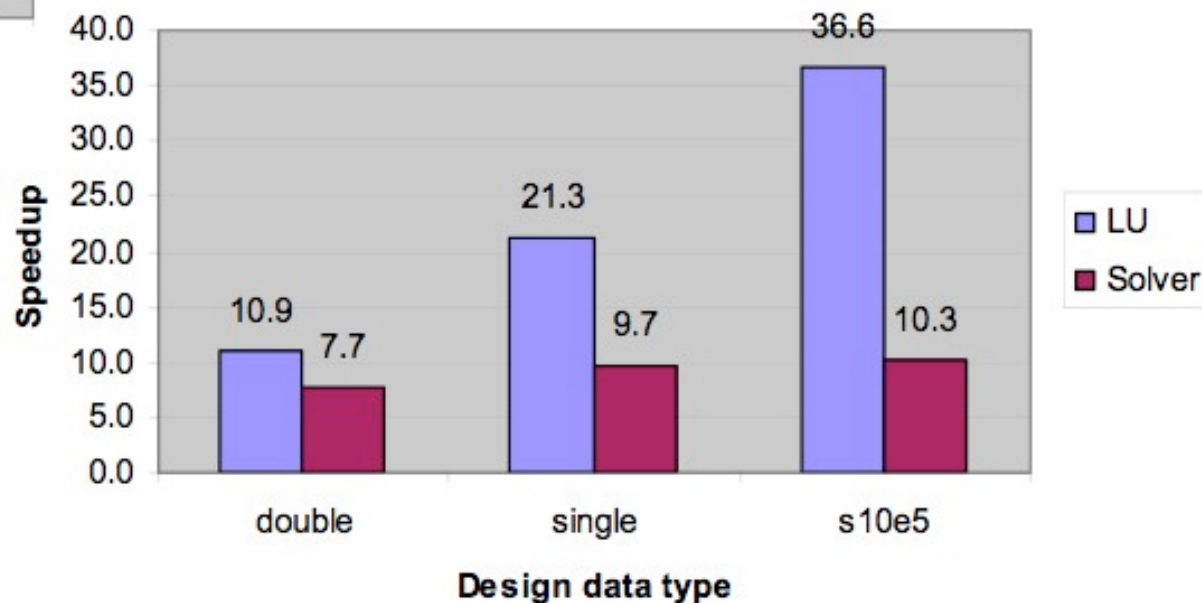


Table 6: LU implementation on XC2VP50-7

Design	Double FP	Single FP	S10e5
PE amount	8	16	32
Max size	128	256	256
Achievable Frequency	120MHz	150MHz	150MHz
Slices	27,005 (57%)	14792 (59%)	14730 (62%)
BRAMs	68 (29%)	129 (55%)	65 (28%)
MULT18X18	128 (55%)	64 (27%)	32 (13%)



*Virtex-II vs 2.2 GHz Opteron

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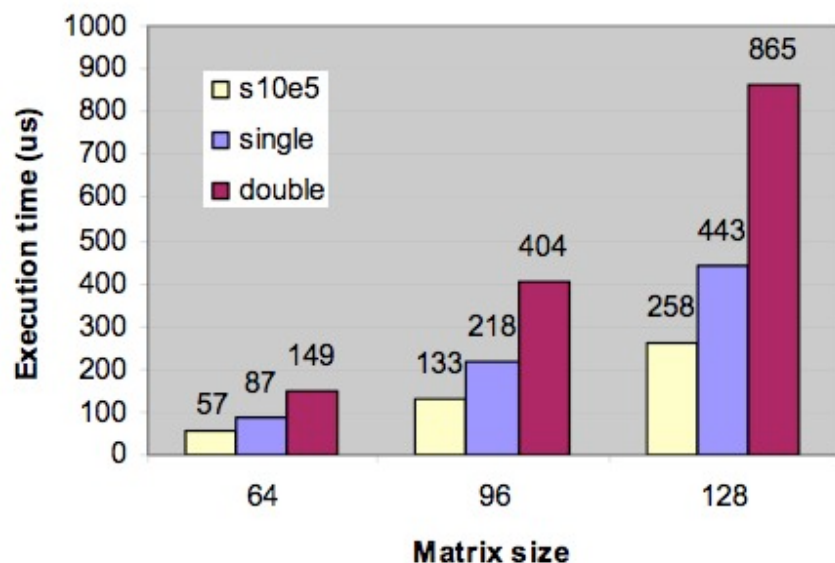
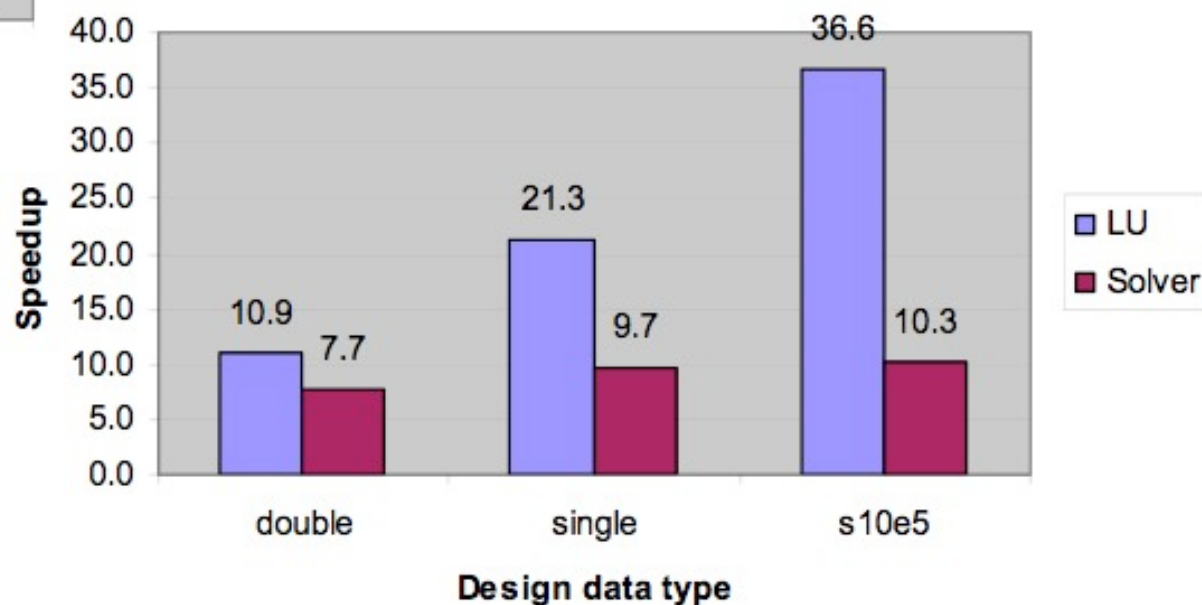


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Benefits:

- High performance of LP arithmetic
- High precision accuracy
- Speedup increases with matrix size (LU dominates calculations)



*Virtex-II vs 2.2 GHz Opteron

37x* LU Decomposition FPGA Speedup 10x for Matrix Equation Solver

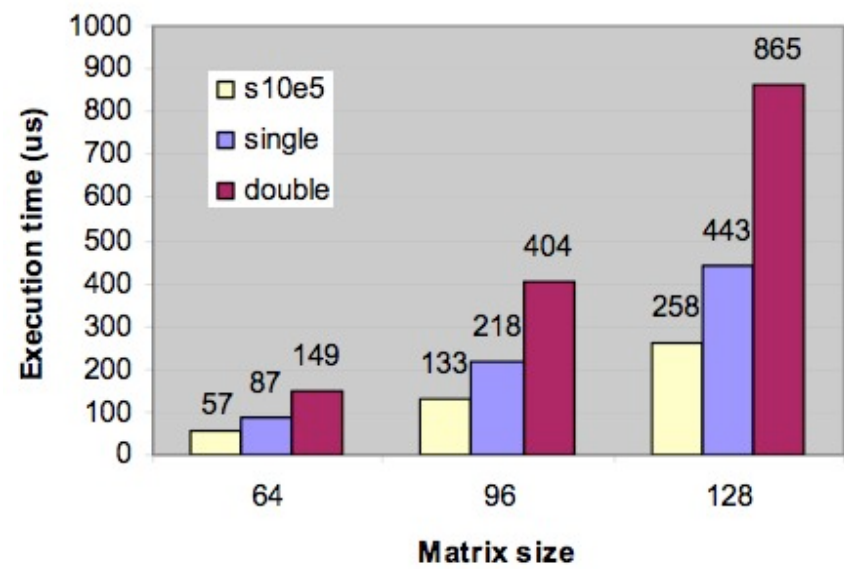
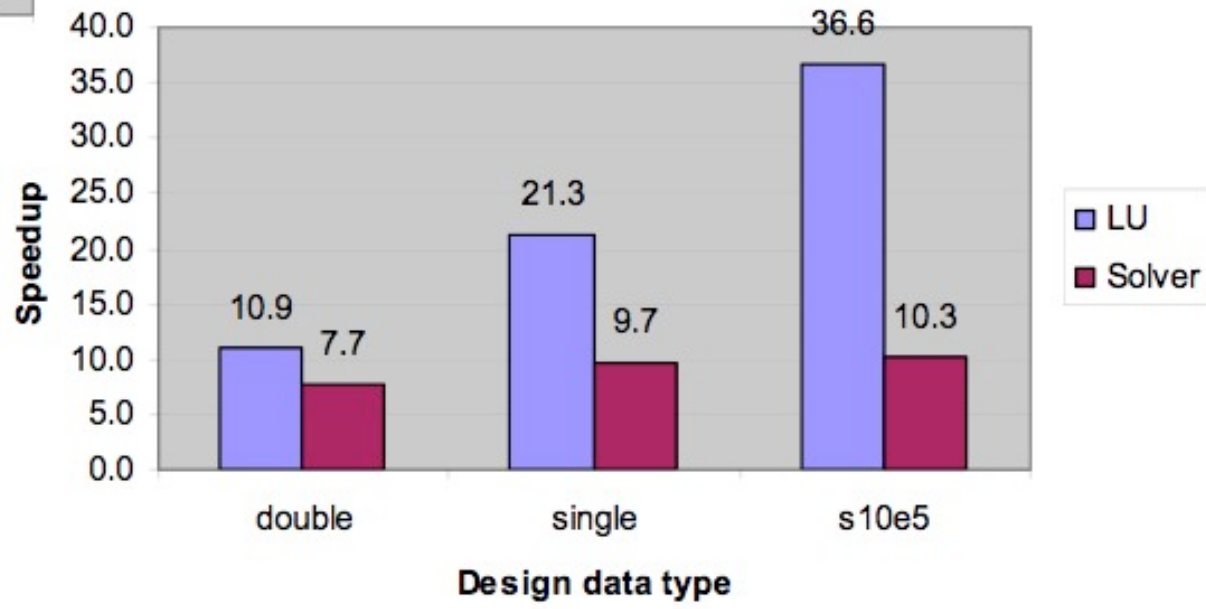


Table 6: LU implementation on XC2VP50-7

Design	Double FP	Single FP	S10e5
PE amount	8	16	32
Max size	128	256	256
Achievable Frequency	120MHz	150MHz	150MHz
Slices	27,005 (57%)	14792 (59%)	14730 (62%)
BRAMs	68 (29%)	129 (55%)	65 (28%)
MULT18X18	128 (55%)	64 (27%)	32 (13%)



Benefits:
High performance of LP arithmetic
High precision accuracy
Speedup increases with matrix size
(LU dominates calculations)

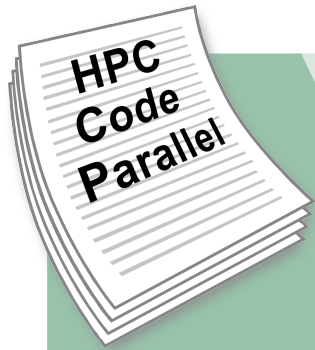
First mixed-precision LU & solver for FPGAs

*Virtex-II vs 2.2 GHz Opteron

Ported Weather-Climate code Spectral Transform Shallow Water Model (STSWM) to **FPGAs**



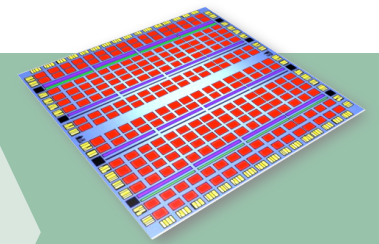
Ported Weather-Climate code Spectral Transform Shallow Water Model (STSWM) to **FPGAs**



Profile-Develop
HLL

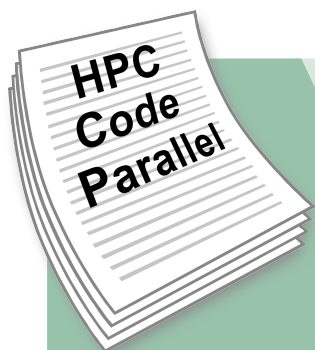


HLL compiler
CHiMPS, Mitrion
(FPGA Tools Inside)



FPGA
speedup

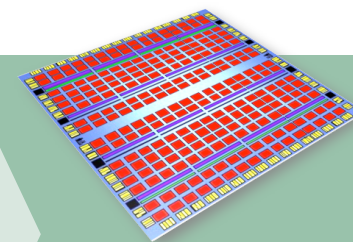
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Profile-Develop HLL

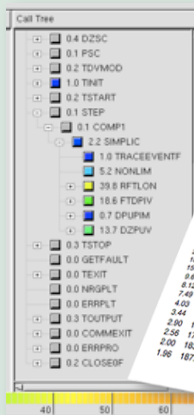


HLL compiler
CHiMPS, Mitrion
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FPGA speedup

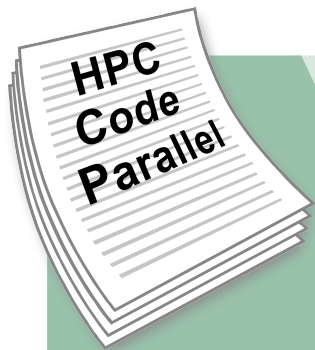
Profile



For profile:
Data sample source as 0.01 seconds.

% cumulative	self	self	total	%	
time	seconds	seconds	calls	calls	
			local	name	
20.80	40.07	11	3.64	5.23	errand_
18.82	76.84	36.27	129	0.28	vpassm_
15.40	106.00	29.66	10	2.97	fitmoo_
9.02	124.65	18.55	11	1.69	shrms_
8.12	140.19	15.64	11	1.42	shlyrc_
7.49	154.48	14.43	33	0.44	ms9d_
4.02	162.39	7.77	1	7.77	192.64 MAIN_
3.44	169.01	6.62	1	6.62	6.74 cald_
2.90	174.59	5.58	1	5.58	8.12 dx_
2.28	179.52	4.93	10	0.49	10.22 advect_
2.00	183.37	3.85	10	0.39	0.39 ms9a_
1.98	187.15	3.78	356	0.01	0.01 ordlog_

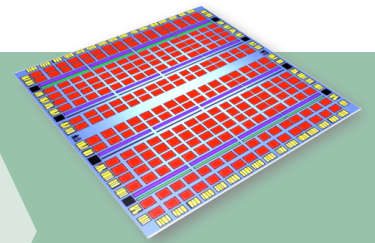
Ported Weather-Climate code Spectral Transform Shallow Water Model (STSWM) to FPGAs



Profile-Develop HLL

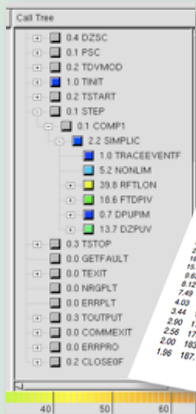


HLL compiler
CHiMPS, Mitrion
(FPGA Tools Inside)



FPGA speedup

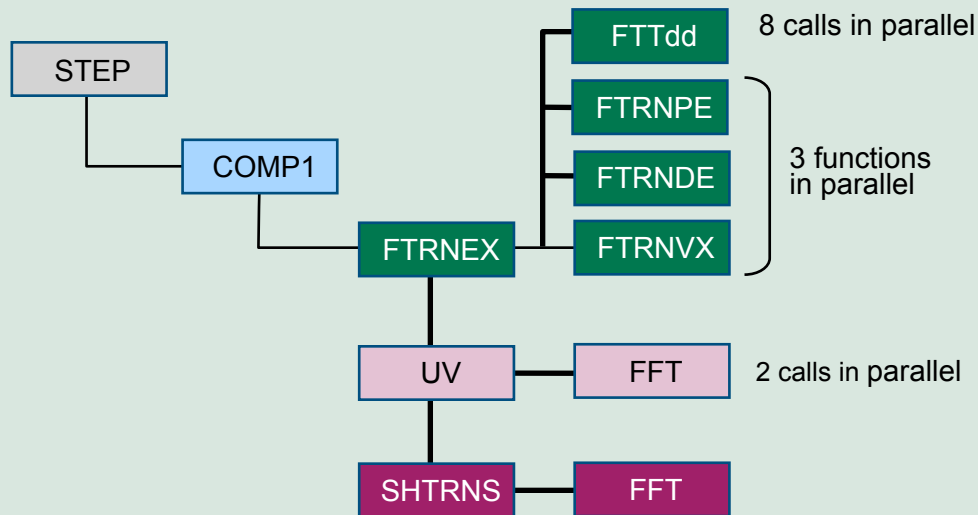
Profile



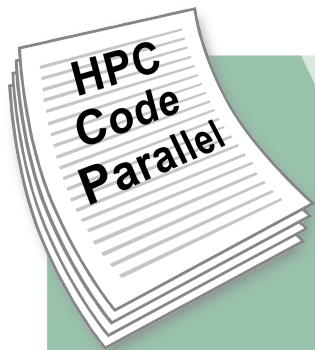
Call profile:
Data sample counts as 0.01 seconds.

% cumulative	self	total	time	seconds	seconds	calls	calls	local	name
20.82	70.07	40.07	11	3.64	5.23	errand...			
18.82	76.24	36.27	129	0.28	0.28	vpassm...			
15.40	106.00	29.66	10	2.97	2.97	fft...			
8.12	140.19	15.64	11	1.69	2.95	shtrns...			
7.49	154.49	14.43	11	1.42	1.74	shtrns...			
4.93	162.39	7.77	33	0.44	0.44	fft...			
3.44	169.01	6.62	1	7.77	192.64	MAIN...			
2.90	174.59	5.58	1	6.62	6.74	calc...			
2.28	179.52	4.93	10	0.49	10.22	advect...			
1.90	183.37	3.85	10	0.39	0.39	fft...			
1.86	187.15	3.78	356	0.01	0.01	ordlog...			

Find parallelism: 80% FFTs



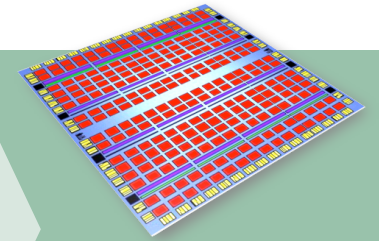
Ported Weather-Climate code Spectral Transform Shallow Water Model (STSWM) to FPGAs



Profile-Develop HLL

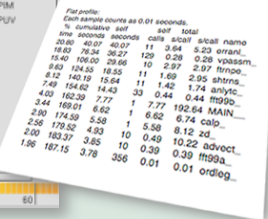
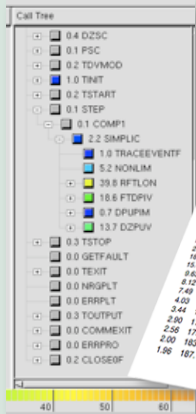


HLL compiler
CHiMPS, Mitrion
(FPGA Tools Inside)

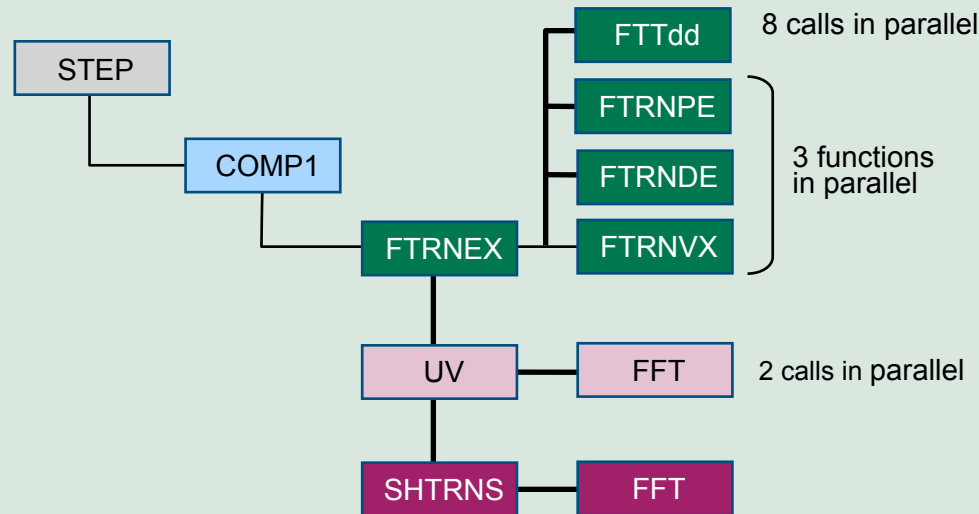


FPGA speedup

Profile

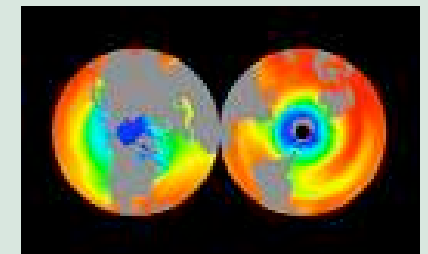


Find parallelism: 80% FFTs



Goal

More GF/\$ GF/Watt



Model 5-10X faster

Summary



- ORNL FPGA research:

Acknowledgment: This is a work of the U.S Government (public domain) supported by the Office of Science, U.S. Department of Energy Contract DE-AC05-00OR22725

The authors thank the US Naval Research Laboratory for access to the 150 FPGA Cray XD1

Summary



- **ORNL FPGA research:**
 - **HPC relevance increasing**
 - **Partners:** *Cray, Xilinx, UT, Mitrion, NRL, SGI*

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 - Speedup: **10X** Eqn Soln, **100X** DNA Sequencing
 - Scalable: **7350X** Speedup for 150 FPGAs (Genomics)

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 - Scalable: **7350X** Speedup for 150 FPGAs (Genomics)
- Next: **Maxwell, CHiMPS & DRC (Cray Module)**

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Contact

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Future Technologies Group

Google **Olaf ORNL**

THANK YOU

Question



Answer

Context



#2

ORNL Jaguar Supercomputer Advances to Second in the World

System is the world's most powerful for open science

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