A Brief History of Computing leading to LHC@home

(from personal experience)

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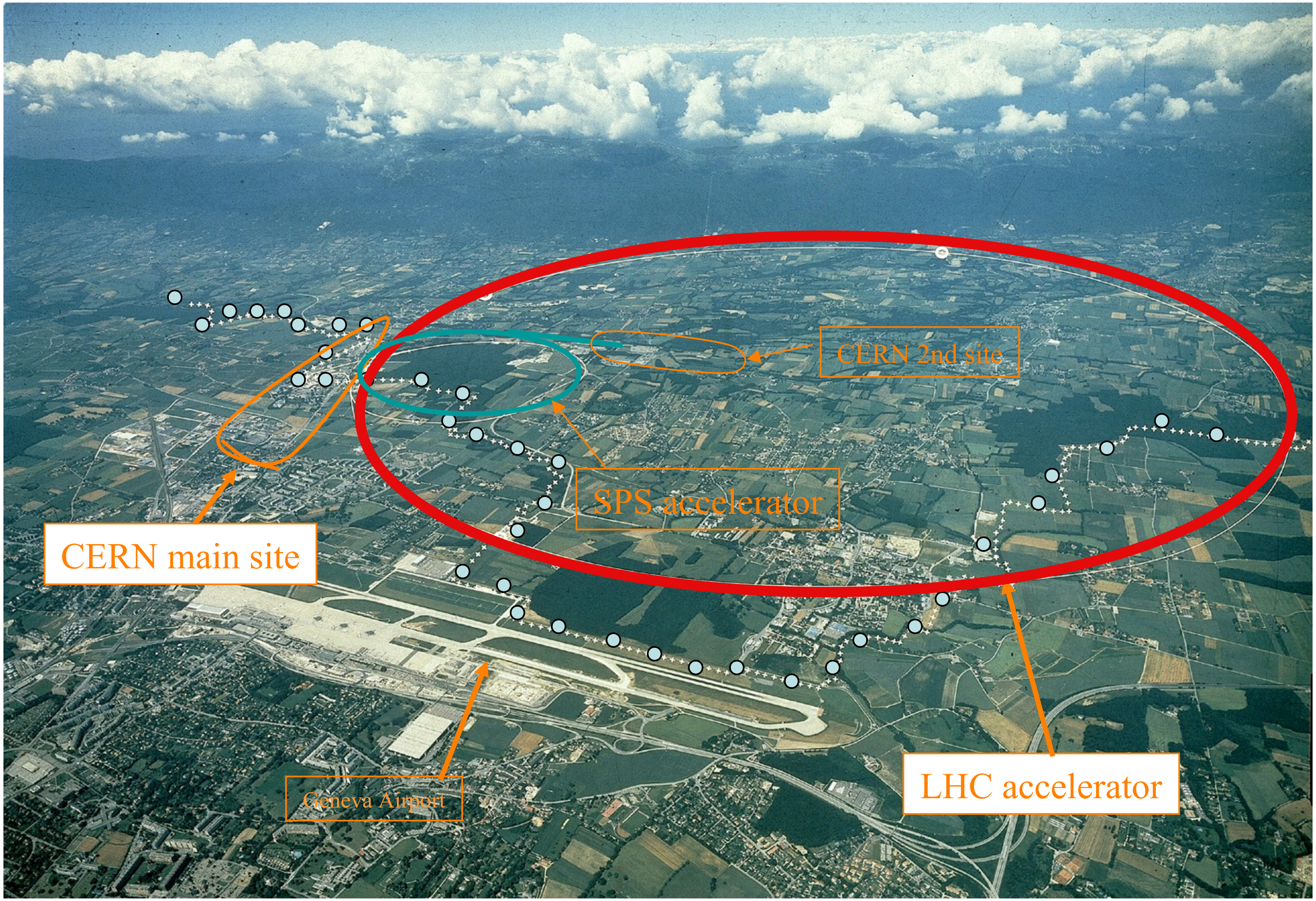
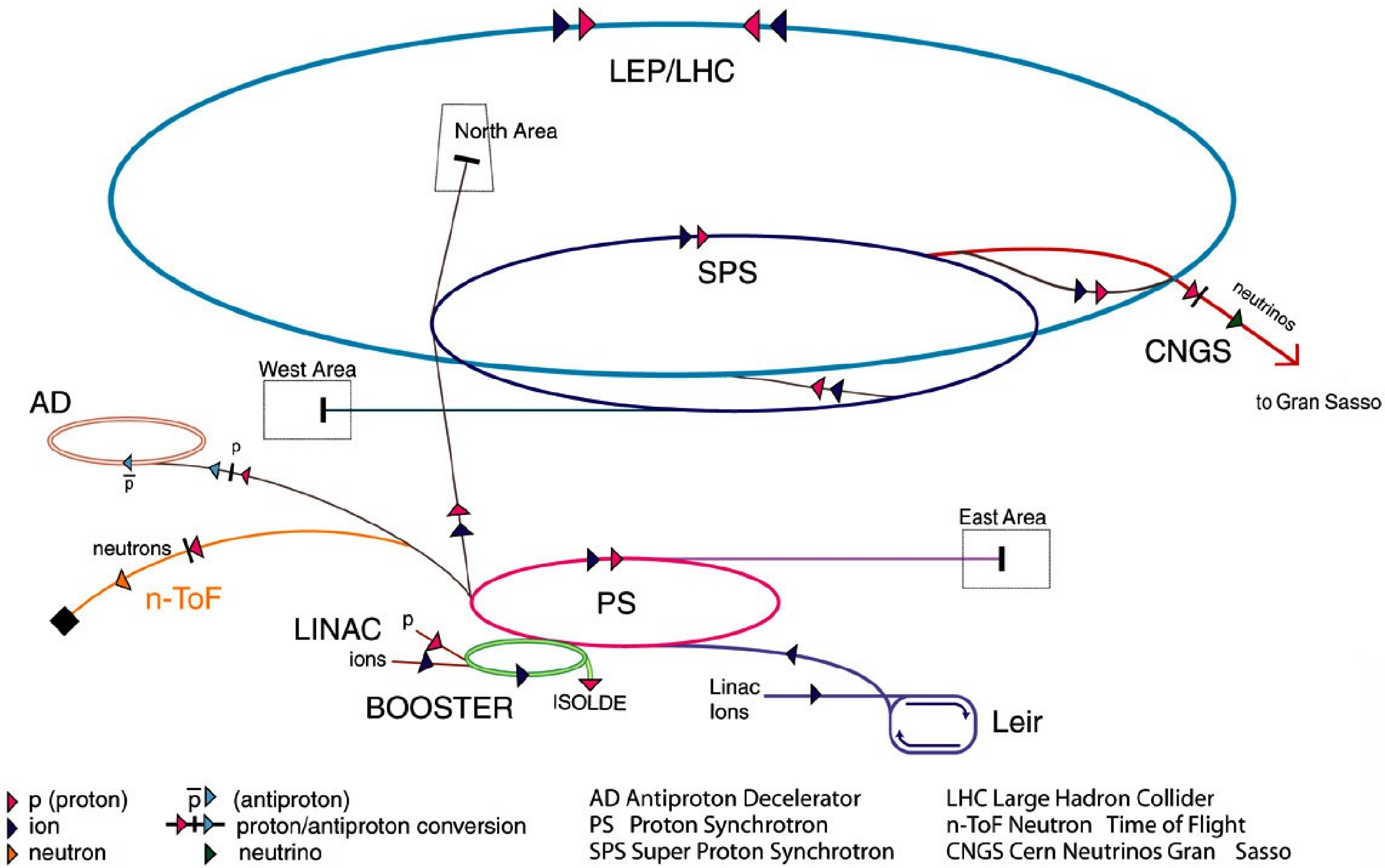
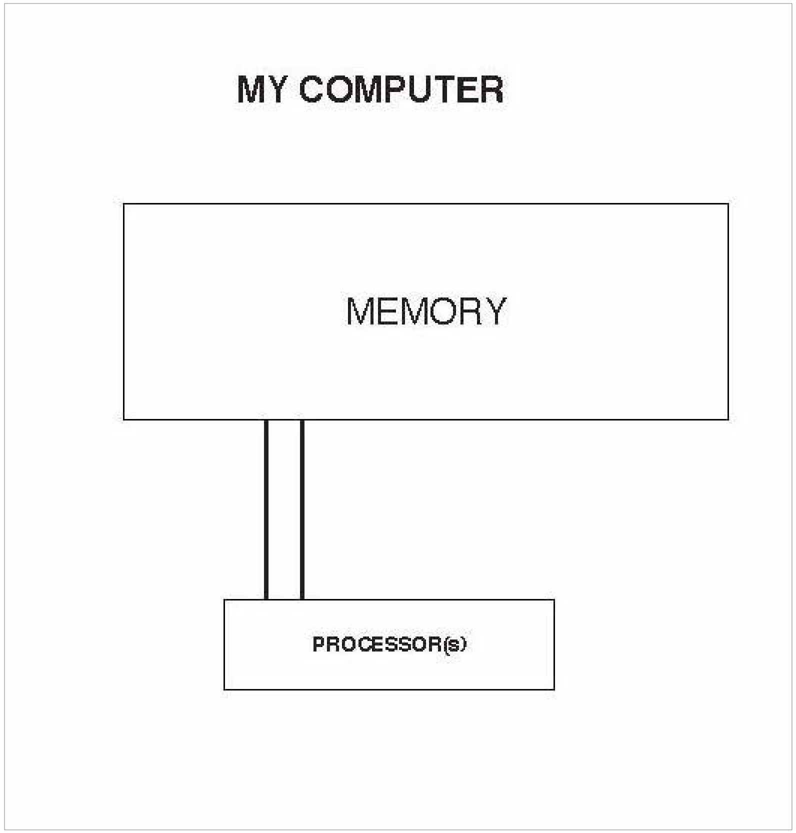
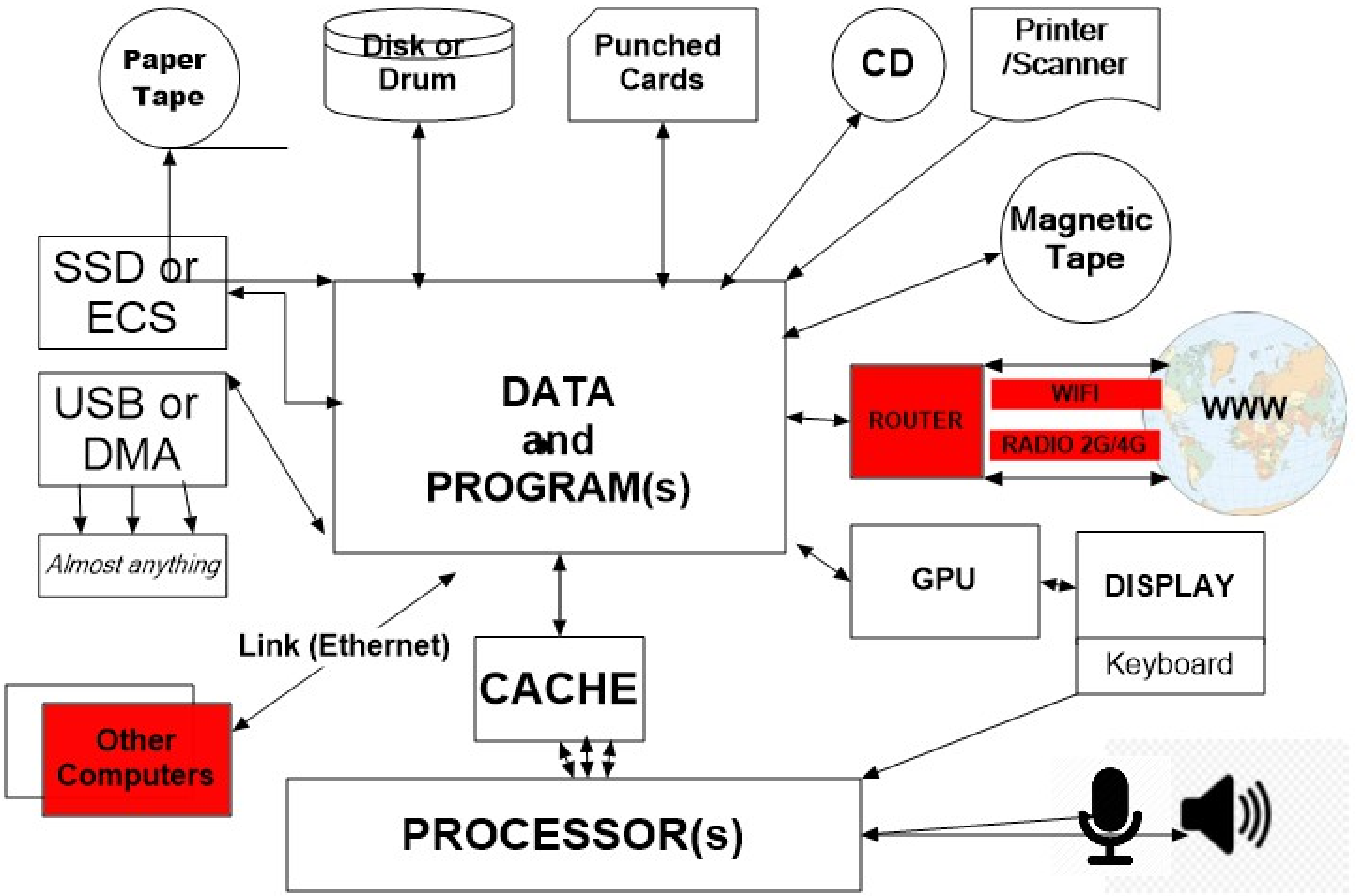

CERN 2nd site
SPS accelerator
CERN main site
Geneva Airport
LHC accelerator

Accelerator chain at CERN, a complex business




MY COMPUTER
MEMORY
PROCESSOR(s)


Paper Tape
Disk or Drum
Punched Cards
CD
Printer /Scanner
Magnetic Tape
SSD or ECS
USB or DMA
Almost anything
DATA and PROGRAM(s)
ROUTER
WIFI
RADIO 2G/4G
WWW
GPU
DISPLAY
Keyboard
Link (Ethernet)
Other Computers
CACHE
PROCESSOR(s)

I/O and NETWORKING

- Eyes, Scanner, Display/screen
- Ears, Microphone, Mouth, Speaker
- Disk, drum, SSD, Magnetic Tape, CD
- Punched Cards and Paper Tape
- Other special devices like HPD
- Just about anything, USB, DMA,....
- NETWORKING!!! The 1960's
- Connect to other computers and the world
  and the World Wide Web, WWW

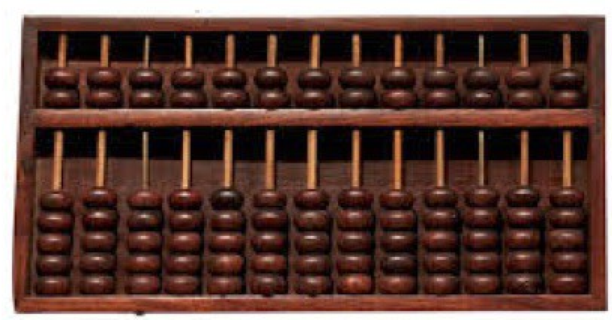
Types of Computer

- Biological i.e.you and me “Wim” Klein
- Mechanical e.g. Abacus, Slide Rule, FACIT (still used in 1960)
- PUNCHED CARDS (Looms and IBM) 19^{th} century already
- ELECTRO-MECHANICAL and ANALOG 20th century
- ELECTRONIC The first ENIAC IN 1937
- TRANSISTORISED 1960 the beginning of a revolution

A couple of mechanical calculators

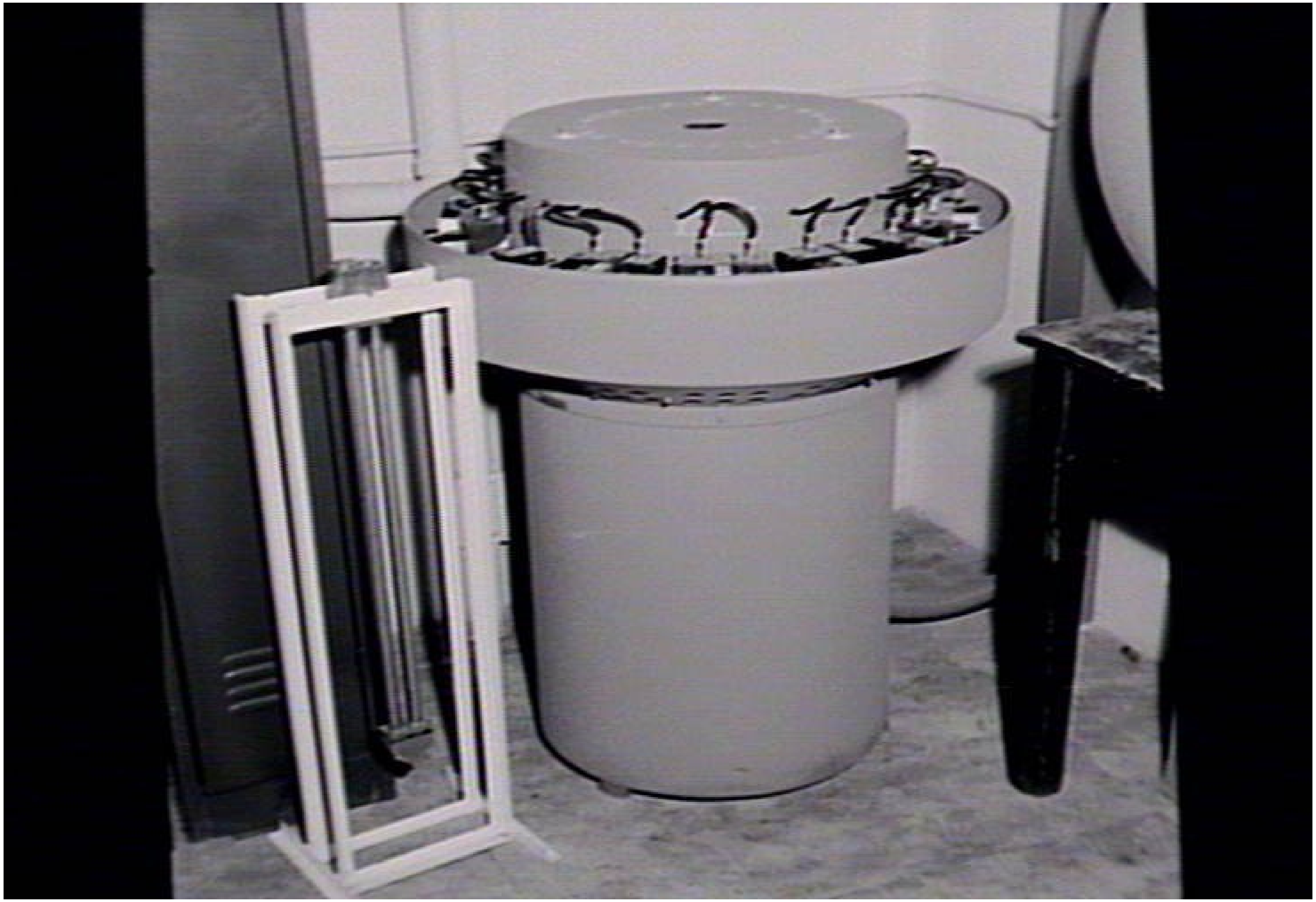
An Abacus (works in 5s) in use for over 3000 years

And a FACIT as I used in 1958.



English Electric Deuce Computer 1960

Mercury Delay Lines



The Revolution

- Many electronic machines from the 1960s onwards
- IBM dominated, but CDC then Cray (the first supercomputer), English Electric, Siemens, Fujitsu, DEC, SUN, H-P, etc etc
- Best shown on the next slides with emphasis on Performance and Price
- The TRANSISTOR, CMOS/Silicon, ???

The EVOLUTION

- Mainframe and SuperComputer
- Minicomputer
- Workstation
- The PC

PARALLELISM

- Basically 2 main types
- Shared Memory or Networked
- OpenMP or MP Thread Parallel
- MPI (PVM) for Networked
- GPU Graphics Processing Unit
- Task Parallel e.g. SixTrack with little or no communication between tasks
- Pipelining/Vectorisation

Networked Computers

- IBM 7090 and 1401 (via magnetic tape)
- CDC 7600 and 6400 and 6500
- CRAY XMP and IBM, CDC, VAX Frontends and Tape Staging
- First centralised data acquisition – VAX to CRAY to IBM to Magnetic Tape
- SHIFT system at CERN

CERN Units

```
 183 Dual 800MHz PIII 256K Cache Linux lxplus028 /2001
>1000 CERN Units per processor in 2019


 20.5 FUJITSU M1800-20 UTS/M FOR77 5/91
 20.3 IBM 9000/900 VM VSFORT OPT(3) XA mode 3/92
 17.1 CRAY C90 (4.16ns) UNIX CFT77 vector 10/92
 16.9 DEC 3000 AXP/400 (133MHz) VMS FTN T3.3 11/92
 15.9 CRAY C90 (4.16ns) UNIX CFT77 scalar 10/92
 15.3 IBM RISC 6000/970 50MHz -O3 hssngl dyn 10/92
 15.1 NEC SX-3 Super-UX f77sx vector 10/91
 14.2 NEC SX-3 Super-UX f77sx 32bit vector 11/92
 14.1 H-P 9000/735 99MHz f77 +O3 -archive 11/92
 13.5 H-P 9000/750 HP-UX f77 -O dynamic 10/92
 13.2 SGI R4000 50MHz Irix f77 -O2 -mips2 dyn 10/92
 12.3 AMDAHL 5990 VM/CMS VSFORT 2 7/88
 11.8 CRAY Y-MP/864 UNIX CFT77 6.0 vector 10/92
 11.5 NEC SX-2 SXOS FORT77SX vector 6/89
```

SixTrack Performance

- To be provided, Pre-processing, Tracking, Post-processing
- One turn, 10,000 steps, many loops over the (60) particles being tracked

LHC (Model) Summary

- 27KM circumference
- Magnets (Dipoles to 20-Pole), Cavities, Beam to Beam, Straight Sections, etc
- ~10,000 elements / steps of 50 types
- A bunch of 30 particle pairs (NOT 10**11)
- Initial conditions in phase space
  - Tune
  - Amplitude
  - Angle

Terminology

- A Study, typically a few thousand or more jobs from 2 to 10 hours CPU, 10**5/6 turns
- Needs LHC physical description, magnet errors, alignment errors.
- A Case (job) has one set of initial values
- Postprocessing is the amalgamation of all the results to define the Dynamic Aperture (from which 10% is subtracted).

The SixTrack Program

- 60,000 lines of standard Fortran 77
- Pre-processing, Tracking, Post-process
- Dimensioned for 60 particles, 30 pairs
- Memory requirement – 64 MegaBytes
- 500KB input – 10KB output (gzipped)
- It is NOT madX, replacing MAD 8/9
- Fortran is a Structured Programming Language, now using Fortran 2008

Computing at CERN

- Dominated by the needs of the experiments
- Accelerator design, a small fraction of the various mainframes (1964 – 1998) and the "PARC" IBM workstation cluster
- In 1997 the LHC Machine Advisory Committee recommended more tracking
- The "Numerical Accelerator Project", NAP luck for me, F. Schmidt, and T. Pettersson

NAP Evolution

- A 10 processor Digital/Compaq Alpha TurboLaser (800 CERN Units)
- Added 10 Workstations (1,300 CUs)
- Overlapped by 20 DUAL 800Mz PIII's (7,200 CUs)
- Today 64 Dual 2.4GHz PCs (51,200 CUs)
- Operated as "Fair Share" of the central Linux LSF Batch system lxbatch

The Idea (not original)

- Studies were still typically 1 tune, 60 seeds, up to 8 amplitudes, and 5 angles
- Use ~10000 Windows desktops at CERN to run SixTrack, a highly optimised LHC tracking program
- SixTrack was standard F77 and part of SPECFP2000 and today almost Fortran 2008
- Only 50KB (500KB) IN and < 2MB (6MB) OUT for ~ 1 to 10 hours CPU – ideal for networked computers
- At least double the tracking capacity and potentially provide an order of magnitude increase for zero financial investment

Initial Problems

- No compatible WINDOWS graphics – just dummied out the HBOOK calls, not required
- CR/LF in Windows – remove them on Linux when retrieving the result
- Lost particle processing 1000 times slower on Digital – check more often for NaNs and Infs

CPSS Project

- A. Wagner CERN/IT/WINDOWS provided a screen saver, Web Server and PERL interfaces for job submission and result retrieval
- SixTrack Checkpoint/Restart
- Transparent (almost) SixTrack run environment on Linux
- Worked well ………until occasional RESULT differences

First real problem

- 1500 jobs, 60 seeds, 5 amplitudes, 5 angles, (v64lhc.D1-D2-MQonly-inj-no-skew) for 10,000 turns
- The final results, the minimum, average and maximum Dynamic Aperture were within 1% of the lxbatch results
- The average DA was within 3 parts in 1000
- Tried 600 seeds/15,000 jobs as final pre-production
- ……BUT…..

Result Comparison

LSF/Linux Results

v64lhc.D1-D2-MQonly-inj-no-skew5 1 11.27 12.20 13.17 15.00
v64lhc.D1-D2-MQonly-inj-no-skew5 2 12.18 13.69 15.46 30.00
v64lhc.D1-D2-MQonly-inj-no-skew5 3 13.90 14.83 16.14 45.00
v64lhc.D1-D2-MQonly-inj-no-skew5 4 16.29 17.32 18.08 60.00
v64lhc.D1-D2-MQonly-inj-no-skew5 5 15.50 16.30 17.34 75.00

Windows CPSS Results

v64lhc.D1-D2-MQonly-inj-no-skew5 1 11.17 12.21 12.97 8.00 18.00
v64lhc.D1-D2-MQonly-inj-no-skew5 2 12.18 13.66 15.24 8.00 18.00
v64lhc.D1-D2-MQonly-inj-no-skew5 3 13.53 14.80 16.09 8.00 18.00
v64lhc.D1-D2-MQonly-inj-no-skew5 4 16.41 17.31 -18.00 8.00 18.00
v64lhc.D1-D2-MQonly-inj-no-skew5 5 15.60 16.30 17.15 8.00 18.00

One bit too many…….

- Careful checking of duplicate results, for one specific seed, identified a difference in the distance in phase space, between a particle pair, when computed on Windows 2000 and on Windows XP.
- Exhaustive (-ing) analysis identified one number 3.756403155274550e-09 was being input as HEX BE3022357D9B0651 on Windows 2000 as compared to HEX BE3022357D9B0650 on Windows XP (and on Linux)

…..but how often? how important?

- 600 fort.16 input files (Multipole Errors)
- 2364 blocks of 40 double-precision numbers
- 100,000 turns each involving 10,000 steps
- Quickly ran 2 times 600 jobs on W2000/XP
- 505 files affected (95 OK) with from 1 to 7 numbers being one bit too large
- Total of 1115 errors in 60 million numbers
  retest with F2003 input conversion

A known problem

- Depends on Compiler/OS
- Could be fixed by (over-)specifying the input values
- Decided to buy the LAHEY-FUJITSU lf95 compiler for WINDOWS (already on Linux) to replace the obsolete COMPAQ compiler
- Surprisingly? Gave “IDENTICAL” results on Windows and Linux

Floating-Point Arithmetic

- Single Precision (SP)
  - 1, 8, 23 (32)
- Double Precision (DP)
  - 1, 11, 52 (64)
- Extended Precision (EP) A mongrel?
  - 1, 15, 64 (80)
- Quadruple Precision
  - 1, 15, 112 (128)
- Arbitrary Precision (Maple, MPFR, etc)

…..more

- 4 rounding modes
- We consider only “round to nearest” _rn
- Double Precision
- ~15 (and a bit) decimal digits
- Range from ~-10**308 to 10**308 but also NaNs and +/- Infinity
- ULP is Unit in the Last (binary) Place

IEE 754 (1985)

- Defines unique reproducible result for +, -, *, /, and sqrt – the correctly rounded result being the floating-point number closest to the exact result
- It is incomplete and open to interpretation
- Needs to be combined with the language standard
- Strict compliance conflicts with performance
- Does NOT cover Elementary Functions
- 60-bit word, 6-bit byte, big/little endian HORRIBLE

Floating-Point issues (Double Precision Extended)

- Extended (internal) 80-bit Precision EP
- (Double) rounding applied arbitrarily
- Fused Multiply Add
- SSE2 OK (but cannot use FMA in recent AVX extensions)
- DISABLE EP, in fact the default with lf95
- (“everything” else is disabled anyway)

EP Disabled

- Must NOT use libm,
- other libraries ????
- May introduce new problems in borderline evaluations
- Could affect performance (convergence)
- I contend that these cases need to be solved otherwise
- (Intel will make it the default! NEVER)

The beam-beam case

- While running some 400,000 2 hour jobs covering 1000 angles to prove CPSS
- Tried a study involving beam-beam interactions over a million turns
- Immediately detected a few result differences between INTEL IA32 and ATHLON AMD64 (also INTEL IA64)
- Traced back to an “exp” function - Not easy, but do-able with binary output
- Abandon the goal of reproducibility??? Abandon the whole idea!!!

Investigation

- Verified that IA64 was same as AMD64 (but see later)
- Found the log function similarly afflicted
- WWW search – insulted on a News Group
- Most problems/solutions eliminated because of the simple code generation
- Found several relevant libraries – MPFR, libultim IBM, libmcr SUN,36 crlibm ENS

The libraries

- MPFR – arbitrary precision – slow
- libultim – 800 bits – too much/not enough
- libcmr – arbitrary precision – slower
- crlibm – double precision – optimised and portable to any IEEE-754 compliant CPU
- Finally adopted CRLIBM from the Ecole Normale Superieur at Lyon

crlibm

- Delivers correctly rounded double precision results for the elementary functions
- Proven to do so
- Performance “comparable” to libm on average Testing now < 2%, not finished
- REQUIRES EP DISABLED
- Really more than I needed

Crlibm functions

- EXP, LOG, LOG10, SIN, COS, TAN
- ATAN, SINH, COSH
- ASIN, ACOS, now available
  - I wrote them and ATAN2 in terms of ATAN
  - NOT proven correctly rounded
- Each function has four rounding modes – nearest, up, down, to zero
- E.g. exp_rn, exp_ru, exp_rd and exp_rz

THE Solution

- Installed crlibm (portable for Linux and Windows with gcc and Lahey-Fujisu C)
- The numerical differences disappeared
- Performance was at worst 10% slower in the most difficult beam-beam case (but on portable code)
- The only subsequent numerical differences have been traced to failing computers (3 desktops and 1 lxbatch)
- The Intel microcode bug (2017)

Some simple test results

- ULP – One Unit in the Last Place of the mantissa of a floating-point number (one part in roughly 10**16)
  - libm/crlibm IA32: 304 differences of 1ULP
  - ibm IA32/IA64: 5 differences of 1ULP
  - libm IA32/AMD64: 7 differences of 1ULP
  - libm IA64/AMD64: 2 differences of 1ULP
  - libm/libm NO EP: 134623 differences of 1ULP
- NO differences with exp_rn
- 1,000,000 exp calls with random arguments (0,1)

…and with lf95

- – lahey/crlibm IA32: 134645 differences of 1ULP
- – lahey IA32/IA64: 7 differences of 1ULP
- – lahey IA32/AMD64: 7 differences of 1ULP
- – lahey IA64/AMD64: 4 differences of 1ULP

- NO differences with exp_rn

crlibm exp performance

Pentium 4 Xeon gcc 3.3 RETEST!!!!!			
	Average	Min	Max
libm	365	236	5528
crlibm	432	316	41484
libultim	210	44	3105632
mpfr	23299	14636	204736

When quadruple precision is not enough – The Table Maker’s Dilemma

- Rounding the approximation of f(x) is not always the same as rounding f(x)
- Worst case for exp(x), x=7.5417527749959590085206221e-10
- Binary example x=1. (52)1 *2-53 exp(x)=1. (52)0 1 (104)1 010101…
- quad (112 bit) approximations : 1. (51)0 1 (60)0 and 1. (51)0 0 (60)1 are both within 1 Quad ULP but which rounded value is nearest?

BOINC

- The Berkeley Open Infrastructure for Network Computing (c.f SETI@home) was suggested by Dr Segal of the IT dep't
- Initial tests were very positive with 200,000 hosts reached very quickly in 2004
- LHC@HOME today – up to 500,000 computers, 1,800,000 CPUs/Threads, typically around 150,000 active tasks
- Beam-beam studies, 600,000 one million turn 10 hour jobs run successfully

BOINC ………

- Some 1,000,000 cases completed
- Every jobs is run twice (at least) and only identical results are accepted (NO EPSILON required)
- Estimate 3% of results are erroneous due to undetected hardware errors, over-clocking, or transmission errors. These results are of course rejected (validation).
- Today, normally less than 1 in 10,000

Chrome File Edit View History Bookmarks People Window Help 100% Sat 08:13 Frederick McIntosh

Project status

lhcathome.cern.ch/lhcathome/server_status.php

Apps Zattoo - Highlight... Cheap & Free inte... Bridge Base Online Swisscom Login MyAva dollar index OneLook Dictiona... Project Managem...

transitioner	boincai01	Running
db_purge	boincai01	Running
Download server	lhcathome-upload	Running
Upload server	lhcathome-upload	Running
feeder	boincai01	Running

Computers

With credit	465864
With recent credit	21835
Registered in past 24 hours	167
Current GigaFLOPS	145879.03

Remote daemon status as of 13 Sep 2019, 13:04:51 UTC

Tasks by application

Application	Unsent	In progress	Runtime of last 100 tasks in hours: average, min, max	Users in last 24 hours
SixTrack	515771	121060	2.3 (0.01 - 211.66)	3786
sixtracktest	135259	11237	1.3 (0.01 - 57.69)	234
CMS Simulation	200	1542	12.65 (0.62 - 18.5)	57
Theory Simulation	198	5568	16.68 (0.03 - 52.13)	110
ATLAS Simulation	3190	11670	20.39 (0.03 - 207.9)	313
Theory Native	18	1929	1.41 (0.01 - 26.52)	36

Upstream server release: 1.0.3
Database schema version: 27028
Task data as of 14 Sep 2019, 5:42:03 UTC

POWERED BY BOINC

C@home: Result summary

50804 results

r state	# results
Inactive	0
Unsent	479239
Unknown	0
n progress	119335
Over	1552230

'Over' results

Outcome	# results
---	0
Success	1469029
Couldn't send	0
Computation error	69578
No reply	8352
Didn't need	3460
Validate error	47
Abandoned	1764

'Success' results

Validate state	# results
Initial	73273
Valid	1374669
Invalid	19137
Workunit error - check skipped	8
Checked, but no consensus yet	1691
Task was reported too late to validate	251

File Delete state	# results
Initial	242377
Ready to delete	0
Deleted	1226652
Delete Error	0
Total files deleted	1226652

'Client error' results

Client state	# results
Downloading	10103
Processing	0
Compute error	18512
Uploading	0
Done	661
Aborted by user	40300

r lhcathome.cern.ch...

Main page

The PARK, the FARM, the CLOUD

- Around one million registered hosts
- Almost 500,000 active/with credit
- Around 1,800,00 CPUs/Threads
- Around 400,000 Windows
- (About 164,000 claim to run Windows XP)11644036440
- 80,000 Linux
- 7,000 Darwin
- Around 100 ARM/Android

The Park, the Farm the Cloud

Around one million registered hosts

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80,000 Linux

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Around 100 ARM/Android

- Am I obsessed about a numerical difference of 1ULP?
- It IS a problem for tracking studies, weather/climate prediction and other “chaotic” applications such as molecular systems
- Having eliminated ALL numeric differences SixTrack can be run on any IEEE 754 compatible hardware with identically replicated results (reportedly “probably impossible”)

A Quote

Unfortunately, when it comes to floating-point arithmetic, the goal is virtually impossible to achieve. The authors of the IEEE standards knew that, and they didn't attempt to achieve it (i.e. Identical results).

As a result, despite nearly universal conformance

to (most of) the IEEE 754 standard throughout

the computer industry, programmers of portable

software must continue to cope with

The next steps

- Extend to other C/C++ C99 compliant applications and compilers and GAMES? And Sixtracklib
- Already ported to Intel/AMD, Apple, ARM/ANDROID, Raspberry PI, IBM Power Series, GPUs, Linux, Windows, MacOS, PCs ffrom Pentium 3 onwards
- ALWAYS MAINTAIN IDENTICAL DOUBLE PRECISION FLOATING-POINT RESULTS …... 0 ULP DIFFERENCE