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Mineure CalHau1

A short overview of High Performance Computing

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What is « HPC » ?

High performance hardware

Numerical algorithms

- Serial optimization – tilling
- Vectorization
- Multithreading
- Message passing

Parallel programming

Intensive computing & large scale applications

→ **High Performance Computing** → TeraFlops, PetaFlops, ExaFlops

High Performance Computing → **« HPDA »**

- - - - - **Big Data** → TeraBytes, PetaBytes, ExaBytes

Big Data → **« HPDA »**

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High Performance Hardware

Inside ….

… high performance hardware

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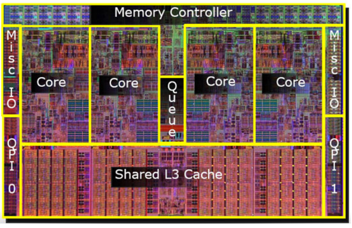
High Performance Hardware

From core to SuperComputer



Computing cores

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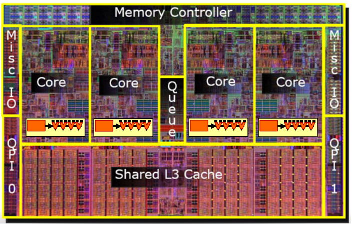
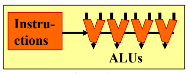
High Performance Hardware

From core to SuperComputer



Computing cores
with vector units



Unités AVX

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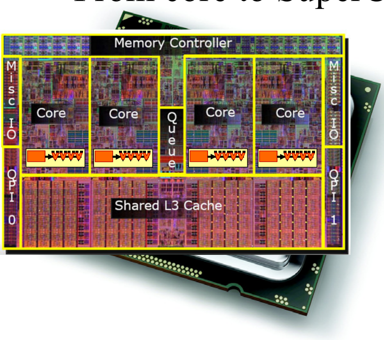
High Performance Hardware

From core to SuperComputer



Computing cores
with vector units

Multi-core
processor

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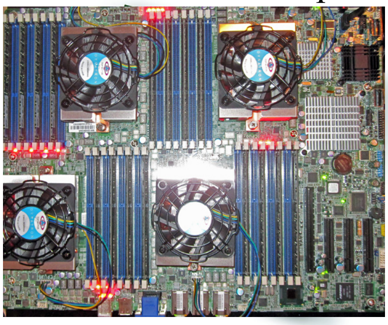
From core to SuperComputer



Computing cores with vector units

Multi-core processor

Multi-core PC/node

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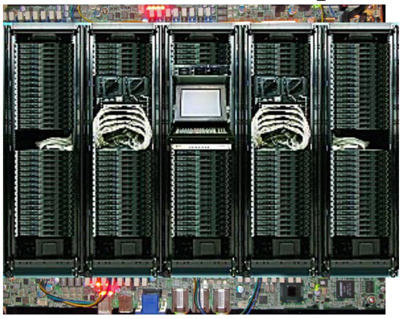
From core to SuperComputer



Computing cores with vector units

Multi-core processor

Multi-core PC/node

Multi-core PC cluster

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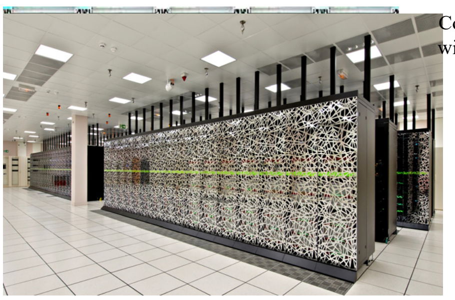
From core to SuperComputer



Computing cores with vector units

Multi-core processor

Multi-core PC/node

Multi-core PC cluster

Super-Computer

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High Performance Hardware

From core to SuperComputer

Computing cores with vector units

Multi-core processor

Multi-core PC/node

Multi-core PC cluster

Super-Computer

+ hardware accelerators

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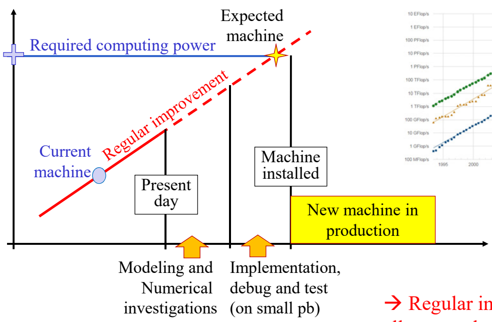
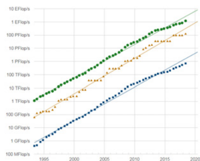
High Performance Hardware

Top500 site: HPC roadmap

High Performance Hardware

Top500 site: HPC roadmap





→ Regular improvement allows to plan the future

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High Performance Hardware

HPC in the cloud ?

Microsoft Azure

« **AZUR BigCompute** »

- High performance nodes
- High performance interconnect (Infiniband)

→ **Customers can allocate a part of a HPC cluster**

aws

- Allows to allocate a huge number of nodes for a short time
- No high performance interconnection network

→ **Comfortable for Big Data scaling benchmarks**

Some HPC or Large Scale PC-clusters exist in some Clouds

But no *SuperComputer* available in a cloud

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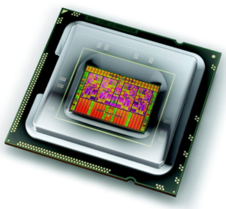
Architecture issues

Why multi-core processors ?



Shared or distributed memory ?

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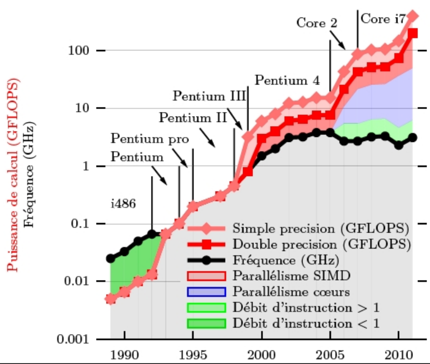
Architecture issues

Re-interpreted Moore's law

Processor performance increase due to parallelism since 2004:



CPU performance increase is due to (different) parallel mechanisms since several years…

… and they require explicit parallel programming

W. Kirshenmann EDF & EPI AlGorille, d'après une première étude menée par SpiralGen

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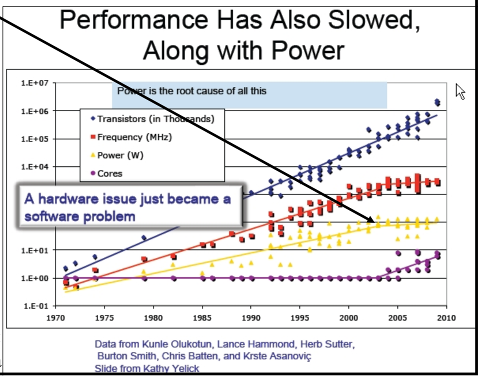
Architecture issues

Re-interpreted Moore's law

Impossible to dissipate so much electrical power in the silicium



Auteur : Jack Dongara

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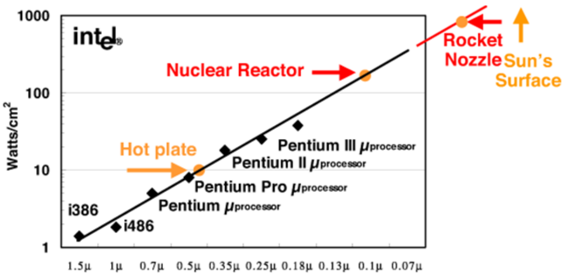
Architecture issues

Re-interpreted Moore's law



It became impossible to dissipate the energy consummed by the semiconductor when the frequency increased !

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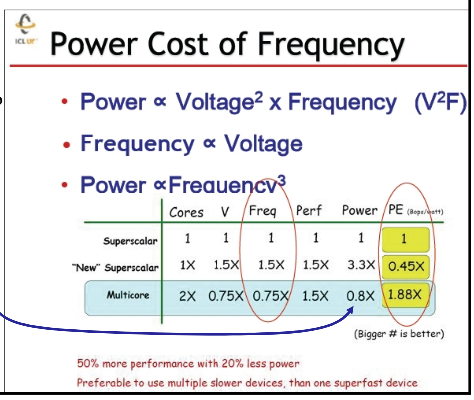
Architecture issues

Re-interpreted Moore's law

To bound frequency and to increase the nb of cores is energy efficient

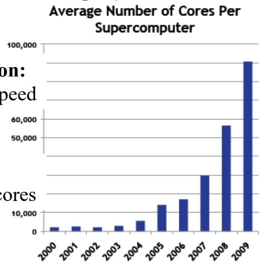
$2\times0.75^3 = 0.8$



Auteur : Jack Dongara

Re-interpreted Moore's law

Initial (electronic) Moore's law:
each 18 months → x2 number of transistors per µm²



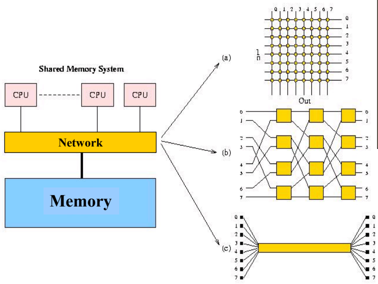
Previous computer science interpretation:
each 18 months → x2 processor speed

New computer science interpretation:
each 24 months → x2 number of cores

Leads to a massive parallelism challenge:
to split many codes in 100, 1000, ….. 10^6 threads … 10^7 threads!!

3 classic parallel architectures

Shared-memory machines (*Symetric MultiProcessor*):

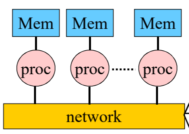


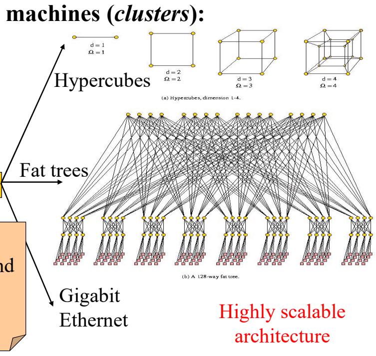
One principle:
- several implementations,
- different costs,
- different speeds.

Overview *of Recent Supercomputers*
Aad J. van der Steen
Jack J. Dongarra

3 classic parallel architectures

Distributed-memory machines (*clusters*):





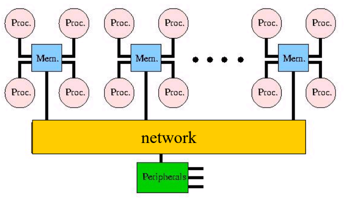
Cluster basic principles, but cost and speed depend on the interconnection network !

Highly scalable architecture

Architecture issues

3 classic parallel architectures

Distributed Shared Memory **machines (DSM):**



cache coherence Non Uniform Memory Architecture (**cc**NUMA)

Extends the cache mechanism

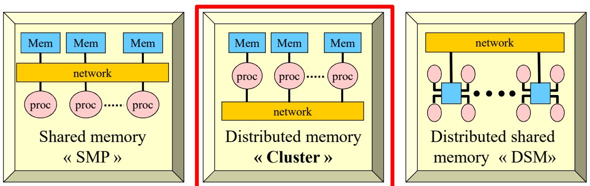
Up to 1024 nodes
Support global multithreading

Hardware implementation: fast & expensive…
Software implementation: slow & cheap !

Overview *of Recent Supercomputers*
Aad J. van der Steen
Jack J. Dongarra

Architecture issues

3 classic parallel architectures



- Simple and efficient up to … 16 processors. Limited solution
- Unlimited scalability. But efficiency and price depend on the interconnect.
- Comfortable and efficient solution. Efficient hardware implementation up to 1000 processors.

2016 : almost all supercomputers have a cluster-like architecture

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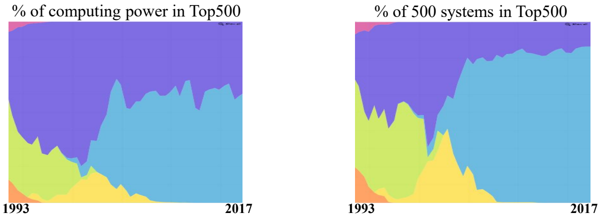
Architecture issues

Evolution of parallel architectures

% of computing power in Top500 — % of 500 systems in Top500



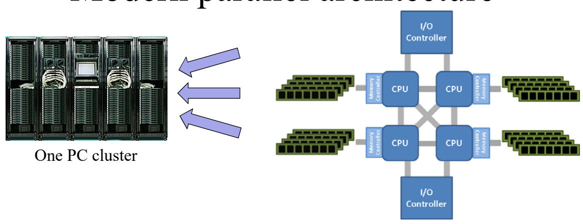
Pure SIMD — SMP — MPP (cluster with custom interconnect)
Single processor — ShM vector machine — Cluster

2016 : almost all supercomputers have a cluster-like architecture

BUT … →

Architecture issues

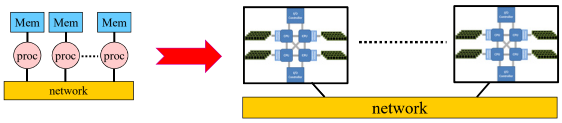
Modern parallel architecture



One PC cluster

Cluster architecture:

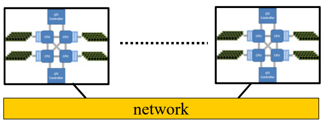
One NUMA node



Architecture issues

Modern parallel architecture

Cluster of NUMA nodes



Time to access a data in the RAM of the processor

< Time to access a data in a RAM attached to another processor
(several access times exist inside one NUMA node)

< Time to send/recv a data to/from another node

→ « **Hierarchical architecture** »:

→ {data – thread} location become critic

Architecture issues

Multi-paradigms programming

Cluster of multi-processor NUMA nodes with hardware vector accelerators

Hierarchical and hybrid architectures :

→ multi-paradigms programming
(or new *high level paradigm*…)

AVX vectorization:
#pragma simd
+ **CPU multithreading:**
#pragma omp parallel for
+ **Message passing:**
MPI_Send(…, Me-1,…);
MPI_Recv(..., Me+1,…);
+ **GPU vectorization**
myKernel<<<grid,bloc>>>(…)
+ ***checkpointing***

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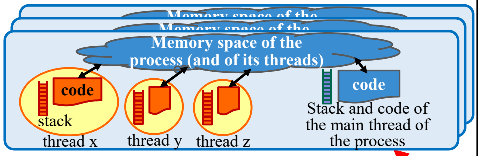
Architecture issues

Distributed application deployment

Distributed Software Architecture

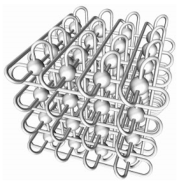


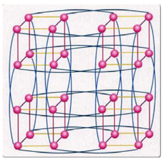
- Achieving **efficient mapping**
  How to map software and hardware ressource ?
- Achieving **fault tolerance**
  Which strategy and mechanisms ?
- Achieving **scalability**
  Are my algorithm, mapping and fault tolerance strategy adapted to larger systems ?

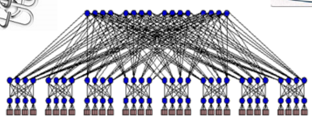
Distributed Hardware Architecture

« Interconnect » (cluster interconnection network)

What is a good interconnection network for a parallel computer ?







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Interconnect

Main features

Main features of a computing cluster interconnect

Sensitive criteria are differents of LAN criteria

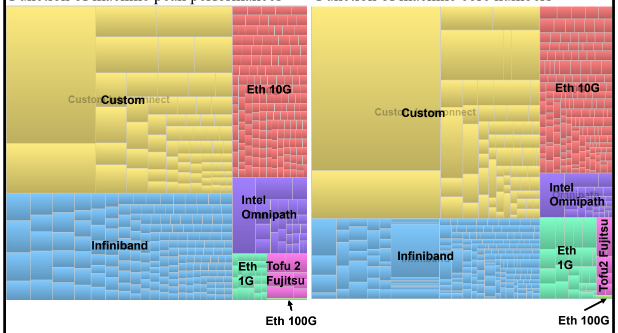
- Bandwidth
- **Latency**
- **Contention & saturation resilience**
  many algorithms are synchronous ones: all nodes compute, and then enter a communication step at the same time
- Performances of *Point-to-Point Communications*
- **Performances of *Collective Communications***
  broadcast, scatter, gather, reduce, all_to_all,…
- **Maximum latency and bandwidth variation between 2 nodes**
- Extension capability (to increase machine size)
  ex : hypercubic topology is hard/expensive to extend

Interconnect

Interconnect in Top500 (nov. 2016)

Function of machine peak performances

Function of machine core numbers

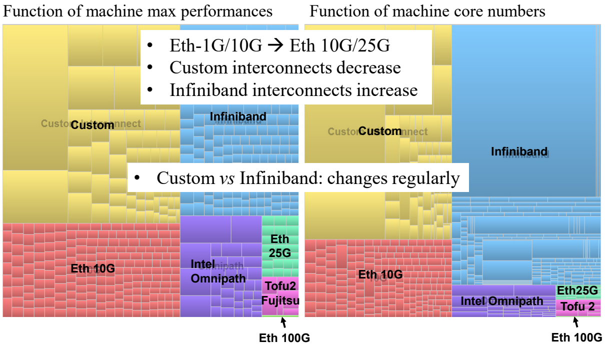


Interconnect

Interconnect in Top500 (nov. 2017)

Function of machine max performances

Function of machine core numbers



- Eth-1G/10G → Eth 10G/25G
- Custom interconnects decrease
- Infiniband interconnects increase

- Custom *vs* Infiniband: changes regularly

Interconnect

10-Gigabit Ethernet *vs* Infiniband

10/25-Gigabit Ethernet :

- Used in many machines in Top500…
  …but not in the most powerful
- High latency
- Cheap interconnect!
- Well known technology (not only in HPC)
  → knowledge already exist in any company/institution

Infiniband :

- Used in many machines in Top500…
  …more powerful machines than Eth-10G machines
- Latency is lower than Eth-10/25G
- More expensive than Eth-10G (25G ?)
- Used only in HPC → special knowledge is required

Watch out: different versions of Infiniband exist, with different perf !

Interconnect

Proprietary custom networks

Proprietary custom networks

- Majors build SuperComputers with their proprietary Interconnect…
  …or customise high quality Infiniband (?)

  CRAY/IBM/Fujitsu/Chinese Supercomputers

- Different networks and network topologies in one machine

  pt-to-pt comm. network, collective comm. network, ctrl network

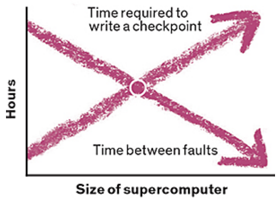
- They are the key component of a SuperComputer

  Ex: Cray T3D has been the first SuperComputer to have an interconnect fast enough for its processor computing power

Fault Tolerance in HPC

Can we run a very large and long parallel computation, and succeed ?

Can a one-million core parallel program run during one week ?



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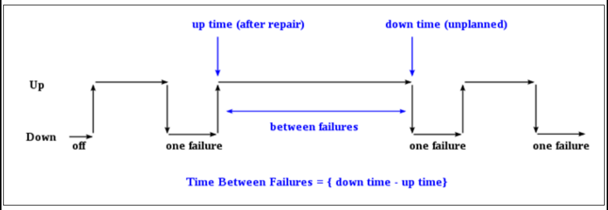
Fault tolerance

Mean Time Between Failures

MTBF definition:



$$\text{Mean time between failures} = \text{MTBF} = \frac{\sum(\text{start of downtime} - \text{start of uptime})}{\text{number of failures}}$$

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Mean Time Between Failures

Experiments:

The Cray-1 required extensive maintenance. Initially, **MTBF was on the order of 50 hours.** MTBF is Mean Time Between Failures, and in this case, it was the average time the Cray-1 worked without any failures. Two hours of everyday was typically set aside for preventive maintenance…. (Cray-1 : 1976)

System Resilience at Extreme Scale
White Paper
Prepared for Dr. William Harrod, Defense Advanced Research Project Agency (DARPA)

Today, 20% or more of the computing capacity in a large high-performance computing system is wasted due to failures and recoveries. **Typical MTBF is from 8 hours to 15 days.** As systems increase in size to field petascale computing capability and beyond, the MTBF will go lower and more capacity will be lost.

Addressing Failures in Exascale Computing
report produced by a workshop on "Addressing Failures in Exascale Computing"
2012-2013

Why do we need fault tolerance ?

Processor frequency is limited and number of cores increases
→ **we use more and more cores**

⇩

We do not attempt to speedup our applications
→ **we process larger problems in constant time !** (Gustafson's law)

⇩

We use more and more cores during the same time
→ **probability of failure increases!**

⇩

We (really) need for fault tolerance
or large parallel applications will never end!

Fault tolerance strategies

High Performance Computing: big computations (batch mode)
→ *Checkpoint/restart* is the usual solution
→ **Complexify src code,** time consumming, disk consumming !

High Throuhgput Computing: flow of small and time constrained tasks
→ Small and independent tasks
→ A task is re-run (entirely) when failure happens

Fault tolerance in HPC remains a « hot topic »

Big Data:
→ Data storage redundancy
→ Computation on (frequently) incomplete data sets …

Different approach !

Who need for fault tolerance ?

In a HPC cluster: computing ressources are checked regularly

→ Wrong ressources are identified and not allocated

→ Many users do not face frequent failures (good!)
(parallel computers are not so bad !)

Which users/applications need for fault tolerance ?

→ When running applications on large numbers of ressources during long times

→ Need to restart from a recent checkpoint

Fault tolerance

Remark:

Critical parallel applications (with strong dead lines)

→ Need for redundant ressources and runs

→ Impossible on very large parallel runs

High availability

Energy Consumption

1 PetaFlops: 2.3 MW !
→ 1 ExaFlops : 2.3 GW !! 350 MW ! ….. 20 MW ?

?

Perhaps we will be able to build the machines,
but not to pay for the energy consumption !!

How much electrical power for an Exaflops ?

1.0 Exaflops should be reached close to 2020:

- 2.0 GWatts with the flop/watt ratio of 2008 Top500 1st machine
- 1.2 GWatts with the flop/watt ratio of 2011 Top500 1st machine
- 350 MWatts if the flop/watt ratio increases regularly
- 20 MWatts if we succeed to improve the architecture ? …
  … « the maximum energy cost we can support ! » (2010)
- 2 MWatts …
  … « the maximum cost for a large set of customers » (2014)

Energy consumption

From Petaflops to Exaflops

1.00 Exaflops : ~~2018-2020~~
2020-2022

25 Tb/s (IO)
20/35 MWatt max….

×1000 perf
× 100 cores/node
× 10 nodes
× 50 IO
× 10 energy
(only × 10)

122 Petaflops : juin 2018

Summit – IBM, Oak Ridge - USA
IBM POWER9 22C 3.07GHz
NVIDIA Volta GV100
2 282 544 « cores »
8.8 MWatt

1.03 Petaflops : June 2008

RoadRunner (IBM)
Opteron + PowerXCell
122440 « cores »
500 Gb/s (IO)
2.35 Mwatt !!!!!!

- How to program these machines ?
- How to train large programmer teams ?

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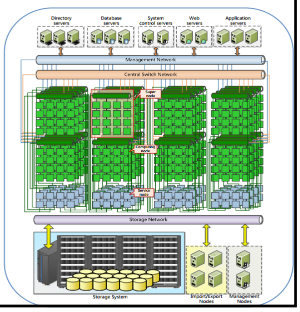
Energy consumption

Sunway TaihuLight - China: N°1 2016 - 2017

93.0 Pflops

- 41 000 processors Sunway SW26010 260C 1.45GHz
  → 10 649 600 « cores »
- Sunway interconnect:
  5-level integrated hierarchy
  (Infiniband like ?)

15.4 MWatt



Energy consumption

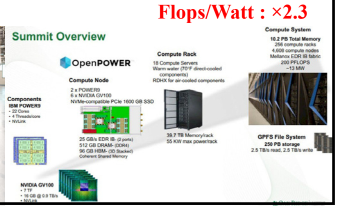
Summit - USA: N°1 June 2018

122.3 Pflops (×1.31)

- 9 216 processors IBM POWER9 **22C 3.07GHz**
- 27 648 **GPU Volta** GV100
  → 2 282 544 « cores »
- interconnect: Dual-rail Mellanox EDR **Infiniband**

8.8 MWatt (×0.57)

Flops/Watt : ×2.3



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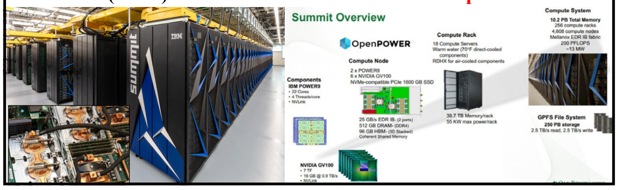
Energy consumption

Summit - USA: N°1 November 2018

143.5 Pflops (×1.54)

- 9 216 processors IBM POWER9 **22C 3.07GHz**
- 27 648 **GPU Volta** GV100
  → 2 282 544 « cores »
- interconnect: Dual-rail Mellanox EDR **Infiniband**

9.8 MWatt (×0.64) **Flops/Watt : ×2.4**



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Energy consumption

What is the sustainable architecture ?

Différentes stratégies s'affrontent dans le Top500 :

- La performance à tous prix avec de gros CPUs très gourmands
  Cray XT6 : 1.7 Pflops, 6.9 Mwatts
  K-Computer : 10.5 Pflops, 12.6 MWatts
- Beaucoup de processeurs moyennement puissants et peu gourmands
  IBM Blue Gene (gamme terminée)
- Utilisation d'accélérateurs matériels : GPU, ~~Xeon-phi~~, …
  → machines hybrides : CPU + accélérateurs
  → difficiles à programmer et pas adaptées à tous les problèmes

Quel est le(s) bon(s) choix pour atteindre l'Exaflops ?

Quel est le choix pertinent pour de « plus petits » clusters ?

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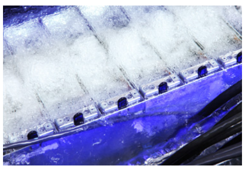
Cooling

Cooling is close to 30% of the energy consumption



Optimization is mandatory!

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Cooling is strategic !

Des processeurs moins gourmands en énergie :

- on essaie de limiter la consommation de chaque processeur
- les processeurs passent en mode économique s'ils sont inutilisés
- on améliore le rendement flops/watt

Mais une densité de processeurs en hausse :

- une tendance à la limitation de la taille totale des machines (en m² au sol)

→ **Besoin de refroidissement efficace et bon marché (!)**

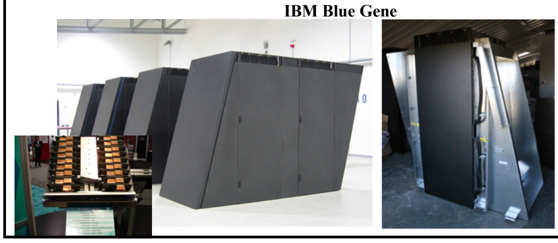
Souvent estimé à 30% de la dépense énergétique!

Optimized air flow

Optimisation des flux d'air : en entrée et en sortie des armoires

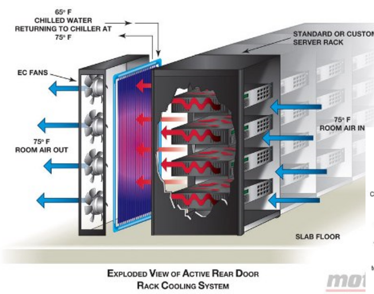
- Architecture Blue Gene : haute densité de processeurs
- Objectif d'encombrement minimal (au sol) et de consommation énergétique minimale
- **Formes triangulaires ajoutées pour optimiser le flux d'air**

IBM Blue Gene



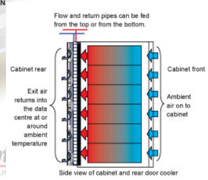
Cold doors (air+water cooling)

On refroidit par eau une « porte/grille » dans laquelle circule un flux d'air, qui vient de refroidir la machine



Exploded View of Active Rear Door Rack Cooling System

Le refroidissement se concentre sur l'armoire.



Side view of cabinet and rear door cooler

Cooling

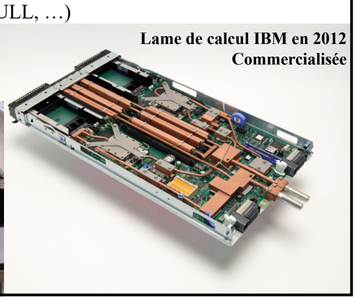
Direct liquid cooling

On amène de l'eau froide directement sur le point chaud, mais l'eau reste isolée de l'électronique.

- Expérimental en 2009
- Adopté depuis (IBM, BULL, …)

Lame de calcul IBM en 2012 Commercialisée

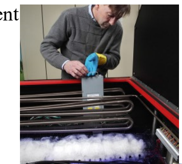
Carte expérimentale IBM en 2009 (projet Blue Water)



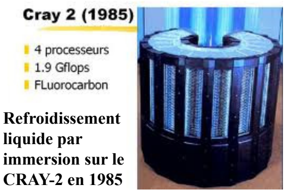
Cooling

Liquid and immersive cooling

Refroidissement par immersion des cartes dans un liquide électriquement neutre, et refroidi.



Refroidissement liquide par immersion testé par SGI & Novec en 2014



Refroidissement liquide par immersion sur le CRAY-2 en 1985

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Cooling

Extreme air cooling

Refroidissement avec de l'air à température ambiante :

- circulant à grande vitesse
- circulant à gros volume

→ Les CPUs fonctionnent proche de leur température max supportable (ex : 35°C sur une carte mère sans pb)

→ Il n'y a pas de refroidissement du flux d'air.

Une machine de Grid'5000 à Grenoble (la seule en *Extreme Cooling*)

Economique !

Mais arrêt de la machine quand l'air ambiant est trop chaud (l'été) !

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Cooling

Extreme air cooling

Refroidissement avec de l'air à température ambiante :

- circulant à grande vitesse
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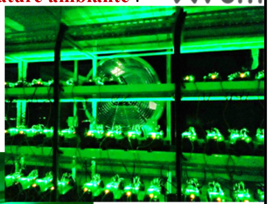

→ Les CPUs fonctionnent proche de leur température max supportable (ex : 35°C sur une carte mère sans pb)

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Installation Iliium à CentraleSupélec à Metz (*blockchain - 2018*)

Economique !

Mais arrêt de la machine quand l'air ambiant est trop chaud (l'été) !

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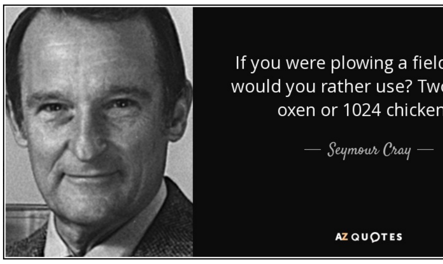
Interesting history of CRAY company



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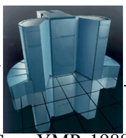
Architecture des machines parallèles

Histoire des ordinateurs CRAY

Cray-1, 1976
133Mflops

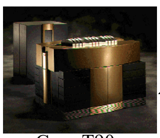
Cray-2, 1985
1.9 gigaflops



Cray-YMP, 1988

Cray-C90, 1991
16 gigaflops

Cray-J90



Cray-T90,
60 gigaflops

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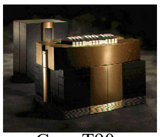
Architecture des machines parallèles

Histoire des ordinateurs CRAY



Cray-T90, 60 gigaflops

Cray-SV1 1 teraflop

NEC (SX)

Accord d'importation

Cray-SX-6

Cray est démembré et semble avoir disparu.

Puis en 2002 un évènement survient ….

Cray-SV2

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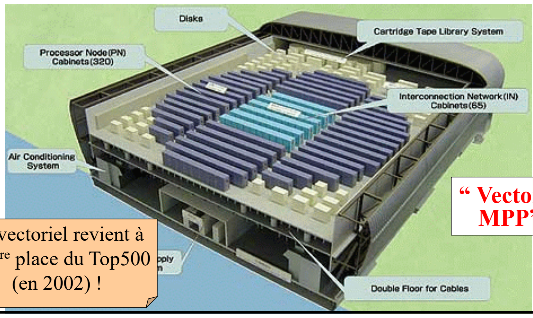
Architecture des machines parallèles

Histoire des ordinateurs CRAY

Apparition du *Earth Simulator* : gros cluster vectoriel NEC :

- 640-nœuds de 8 processeurs : 5120 processeurs
- 40 Tflops crête, a atteint les 35 Tflops en juin 2002



" Vector MPP"

Le vectoriel revient à la 1ère place du Top500 (en 2002) !

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Architecture des machines parallèles

Histoire des ordinateurs CRAY

CRAY

Japan's Impressive Earth Simulator Is As Fast As the Top 20 U.S. Supercomputers Combined

The New York Times

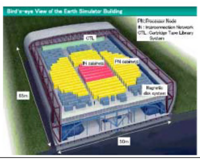
Japanese Computer Is World's Fastest, as U.S. Falls Back

By John Markoff

SAN FRANCISCO, April 19, 2002 — A Japanese laboratory has built the world's fastest computer, a machine so powerful that it matches the raw processing power of the 20 fastest American computers combined and far outstrips the previous leader.

"The first results from the Earth Simulator are stunning. The Earth Simulator will put U.S. scientists at a 10-100 fold disadvantage vis-à-vis their colleagues in Japan. The U.S. has lost the lead in climate science. If we allow the Japanese to deploy [this] strategy uncontested, we will surely lose the lead in other computational disciplines."

Reasserting U.S, Leadership in Scientific Computation, U.S. Department of Energy - Office of Science (June 2002)



"The balance of the computer makes it easier to use."

Forte inquiétude des USA !

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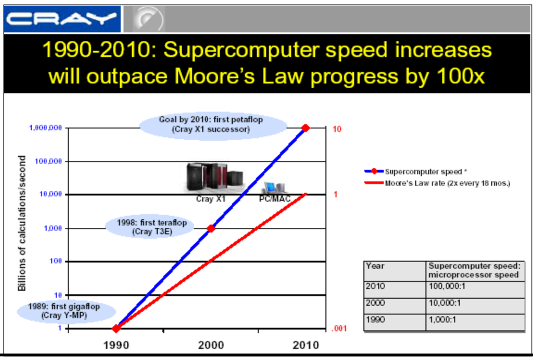
Architecture des machines parallèles

Histoire des ordinateurs CRAY

CRAY était de nouveau là, avec de grandes ambitions:



Year	Supercomputer speed: microprocessor speed
2010	100,000:1
2000	10,000:1
1990	1,000:1

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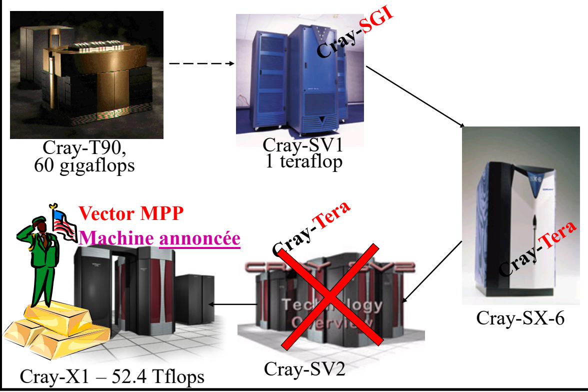
Architecture des machines parallèles

Histoire des ordinateurs CRAY



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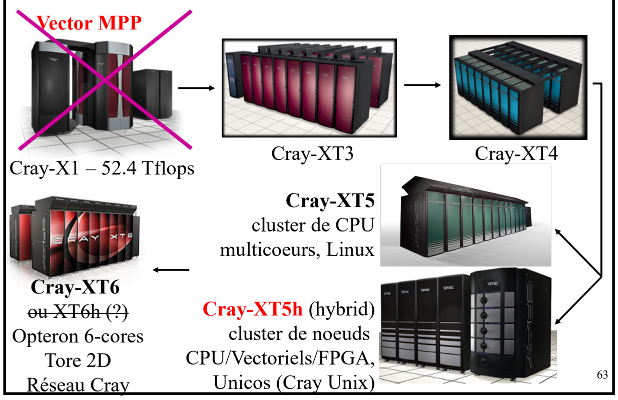
Architecture des machines parallèles

Histoire des ordinateurs CRAY



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Architecture des machines parallèles

Histoire des ordinateurs CRAY

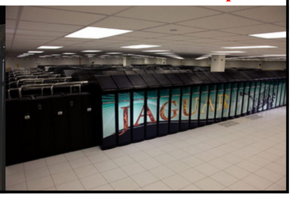
Cray XT6 :

1er au top500 en novembre 2009 : 1.7 Pflops avec 6.9 Mwatt
Architecture : réseau d'interconnexion propriétaire + Opteron 6-cœurs

→ Architectures traditionnelles et très consommatrices d'énergie mais très efficace et sous Linux (logiciels disponibles)

Machine dénommée « Jaguar »

Cray de nouveau à la 1ère place en nov 2009 avec des Opteron



Architecture des machines parallèles

Histoire des ordinateurs CRAY

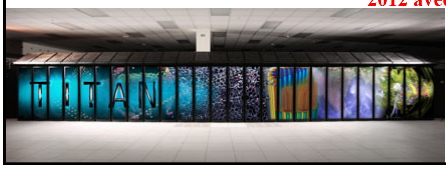
Cray XK7 : entrée des accélérateurs dans la gamme CRAY

1er au top500 en novembre 2012 : 17.6 Pflops avec 8.2 Mwatt

Architecture :

- réseau d'interconnexion propriétaire
- chaque nœud : Opteron 16-cœurs + GPU NVIDIA Tesla K20
- 18688 nœuds → 299008 CPU cores + 18688 GPU K20

Cray à la 1ère place en nov 2012 avec Opteron + GPU



Architecture des machines parallèles

Histoire des ordinateurs CRAY

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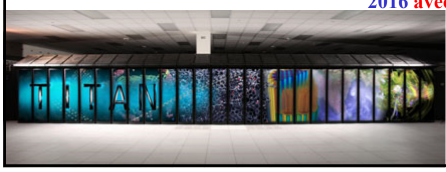
Cray à la 3ème place en juin 2016 avec Opteron + GPU



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A short overview of
High Performance Computing

Questions ?

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