HPC Challenges
in
Oil & Gas Upstream Scientific Applications

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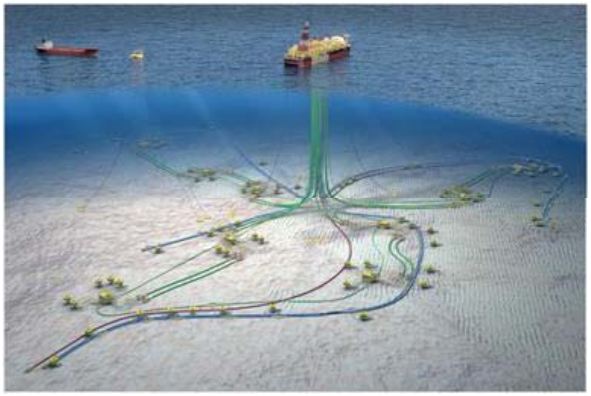
Outline:

HPC Challenges in Oil & Gas Upstream Scientific Applications

- Who are we?
- What is Oil & Gas Upstream?
- What are Oil & Gas Upstream Scientific Applications?
- HPC Challenges
- What are we doing in HPC Research?

Port Arthur refinery, Texas, U.S.A.

Elgin-Franklin platform, North Sea, offshore Scotland, U.K.



Development plan for Dalia Gulf of Guinea, offshore Angola

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Who are we?

- **Total S.A is a publically traded French oil company with ~100,000 employees.**
  ~7,000 at N. America. Right now, ~700 positions opening, globally.
- **Rank 18 by Revenue according to Forbes 2012.**

Rank	Company	Headquarters	Revenue (billion $)	Profits (billion $)	Assets (billion $)	Market Value (billion $)
1	ExxonMobil	USA	433.5	41.1	331.1	407.4
4	Shell	Netherlands	470.2	30.9	340.5	227.6
11	BP	UK	375.5	25.7	292.5	147.4
12	Chevron	USA	236.3	26.9	209.5	218.0
18	Total	France	216.2	15.9	213.0	132.4

- **Total Exploration and Production (E&P) Research & Technology USA**

One of 6 Total E&P Research Centers

- **Seismic Imaging**
- **Engineering & Technology**
  - **Chemical EOR**
  - **Deep Offshore**
  - **Flow Performance**
- **HPC**

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What is Oil & Gas Upstream? (1/2)

- **<u>Upstream</u> is Exploration and Production i.e. find Oil & Gas and produce it.**
- **<u>Downstream</u> is taking Oil & Gas as raw material and make it useful.**
- **1 minute short movie***: (removed by TL due to size of the file is too large)*
  - From several millions years ago to present day
    - The formation of a basin
    - Hydrocarbon (O&G) generation and migration to reservoirs
  - At present day,
    - Seismic boat came in to image the earth
    - Rigs moved in to drill wells

What are Oil & Gas Upstream Scientific Applications?

Three types of Scientific Applications in my terminology:

- *"HTpC"* - High Throughput on (small) parallel Compute : One problem needs to be solved several times. *Distribute (naïve parallel)*
- *"tHPC"* - true HPC : Use entire system to solve ONE problem. *Global (mass parallel)*
- *"pHPC"* - paper HPC : Use HPC to generate data points in "paper" to allow interpolation/extrapolation on the fly. *"Real" time problem.*

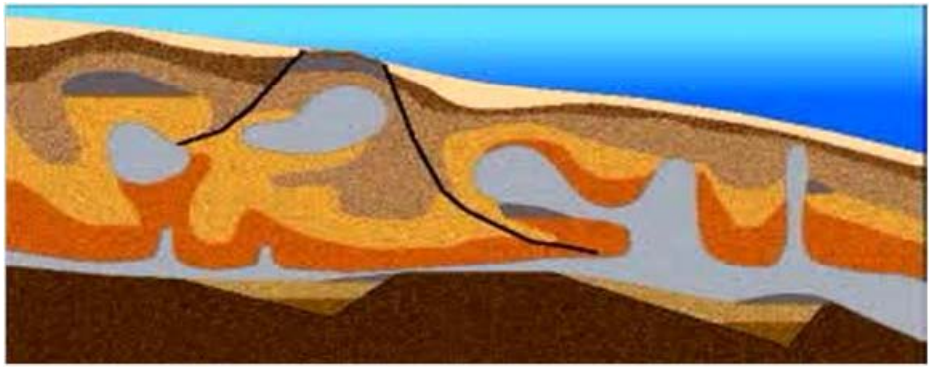
What do we want to know?	Scientific Applications	Compute Character
What does the structure look like?	**Seismic imaging**	***HTpC***
Can there be Oil or Gas or both?	**Basin simulation**	***tHPC***
How to drill wells and how to keep them flowing?	**Engineering applications – drilling and subsurface**	***pHPC***
How to manage the Reservoir?	**Reservoir simulation**	***tHPC***

Seismic Imaging (1/6) – *image the earth*

- **Data Acquisition**

- **Data processing**

- **Interpretation**



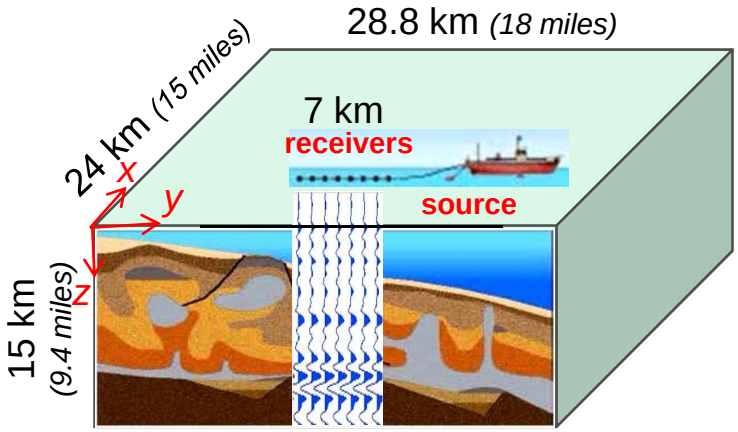
Seismic Imaging (2/6) - Data Acquisitions: *An Example*

- **Acquisition area**
  - 30 blocks (with 3x3 mile^2 or 4.8x4.8 km^2 per block)
    - ~270 mile^2 or 691.2 km^2
    - 24.0x28.8 km for 5x6 blocks, for example,

28.8 km *(18 miles)*

24 km *(15miles)*

Seismic Imaging (2/6) - Data Acquisitions: *An Example*



- **The boat has 10 cables**
  - With 556 receivers per cable *(12.5 m interval).*
  - cable length: 7 km.
  - cable separation: 120 m.
  - cover area of the size 1x7 km.
  - total number of receivers for 10 cables: **5,560**
- **Total number of shots performed: 82,557**
- **Total number of records ("traces") = shots x receivers = 82,557x5,560 = 459,016,920**
- **Each record length is 14.336 seconds with the 4.0ms sampling rate. Yield 3,584 samples per trace.**
- **Total data size = 459,016,920 x 3584 x 4 byte = ~ 6.6TB .**
- **Useful spectra are from 3.5Hz to about 45-50Hz, with depth up to 15km**

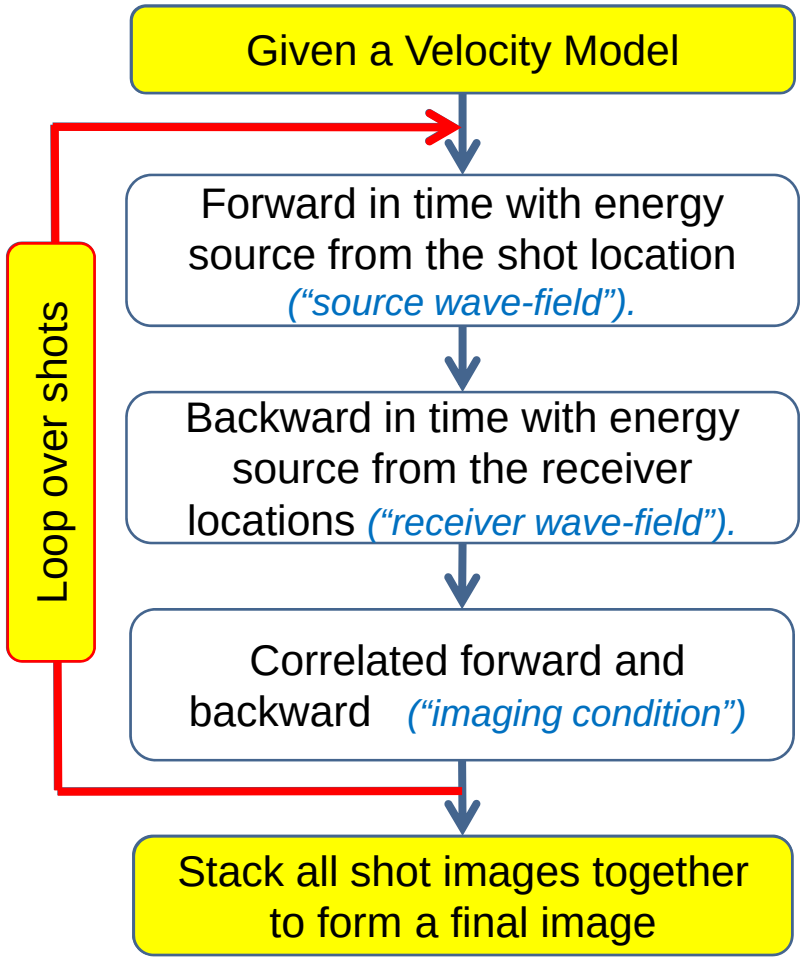
Two infomation here : data from source and data recorded from receivers

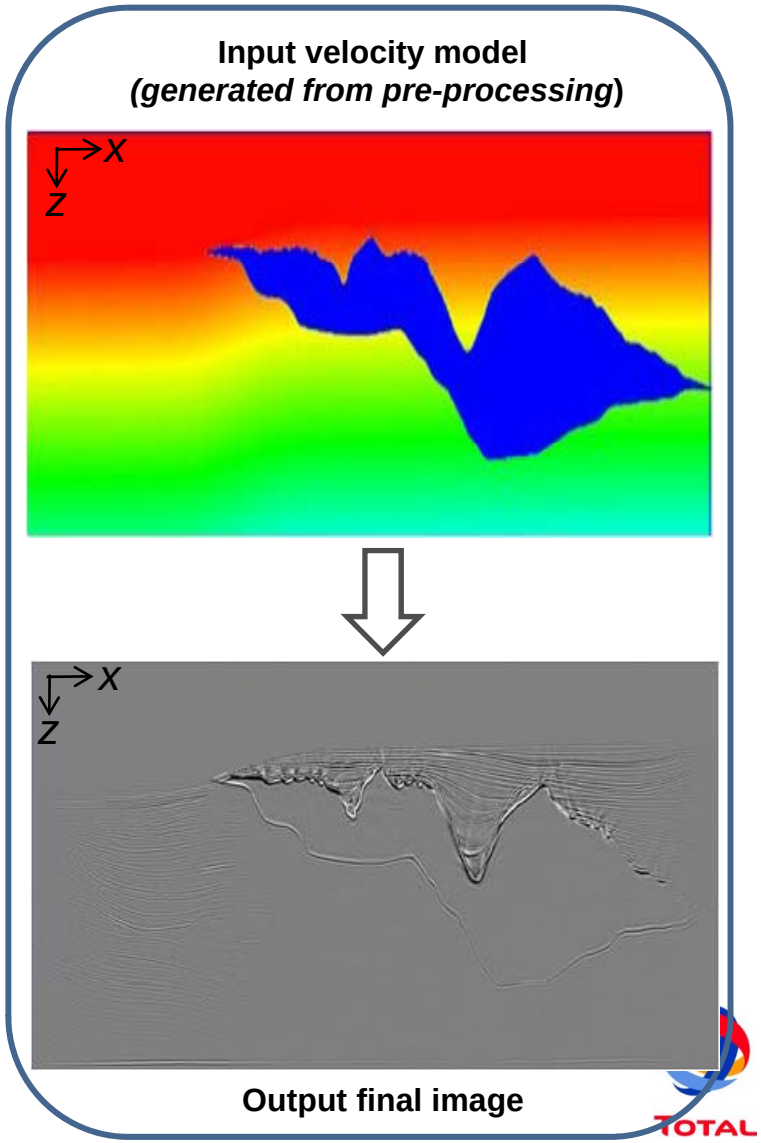
Seismic Imaging (3/6) - Data Processing (1/3)

- **One method we use is called *"RTM"* – Reverse Time Migration.**
  - Currently solve **acoustic** wave equation in a finite difference grid.

$$\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2}$$

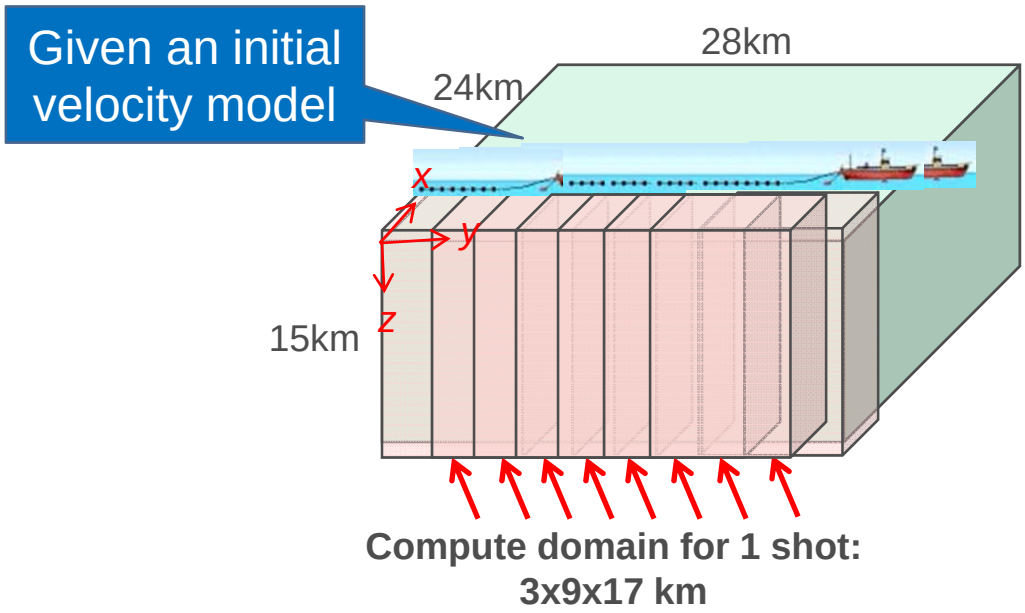
c is the velocity constant:
water ~1500m/s
salt ~5000m/s





Seismic Imaging (4/6) - Data Processing (2/3)

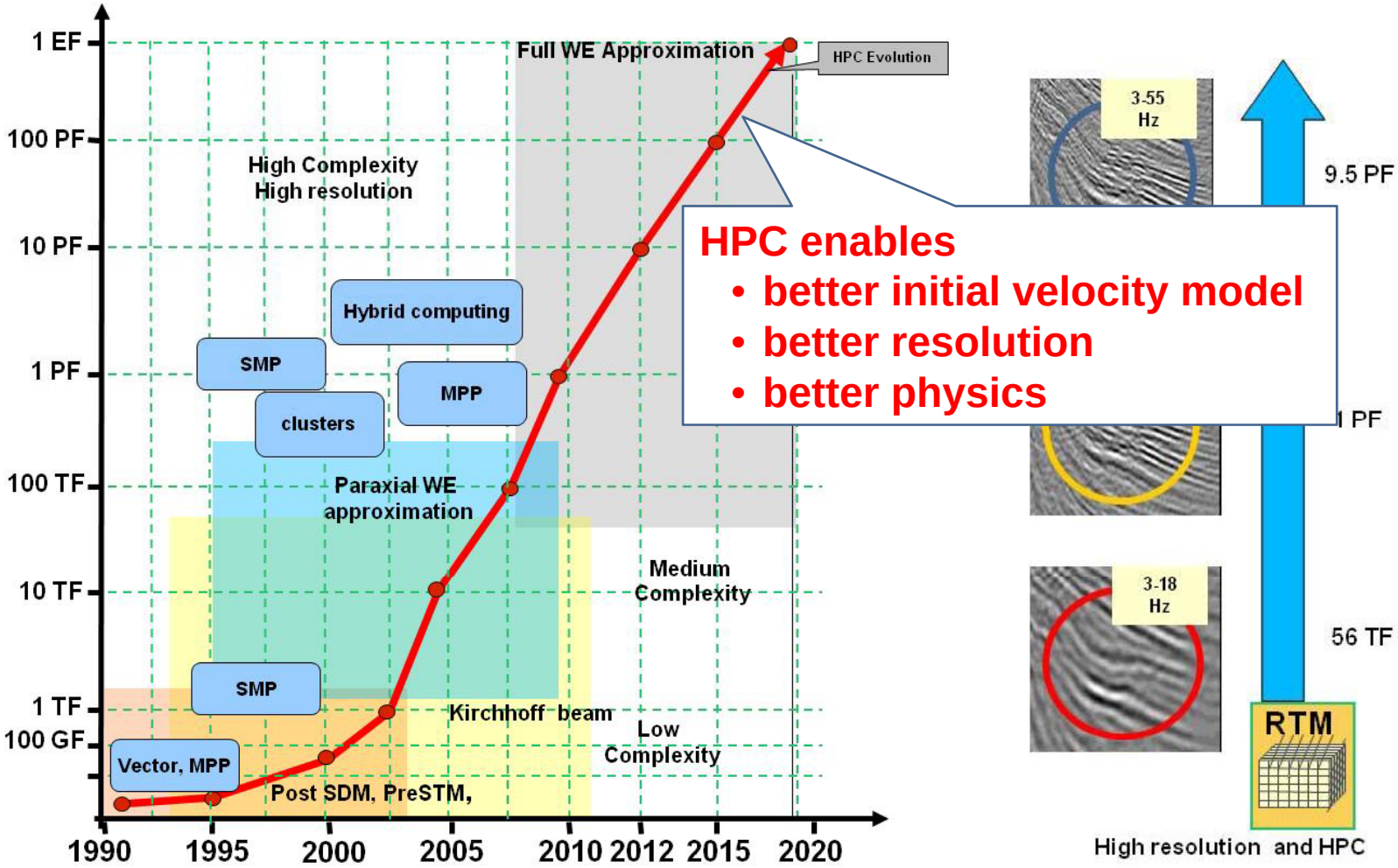
- **Grid size for 1 shot.**
  - compute area: 1x7x15 km + 2x2x2 km (boundary condition padding) = **3x9x17** km
  - grid spacing: dx=25m, dy=12.5m, dz=25m
  - grid size: 120x720x680
  - Single precision: 4 bytes, yield the image size = ~224 MB per shot
- **Total size**
  - **82,557** shots imply total 4.6TB (if we do not partial stack the shots).
  - Model size of 24x28x15 km will have grid size 960x2,240x600 = ~5GB



"HTpC" - High Throughput on small parallel Computing

Seismic Imaging (5/6) - Data Processing (3/3)

Seismic depth imaging Evolution and HPC



HPC enables

- **better initial velocity model**
- **better resolution**
- **better physics**

 From "Seismic Imaging and HPC- how to preserve our investment and to prepare the future?", Henri Calandra, Total, EAGE 2010

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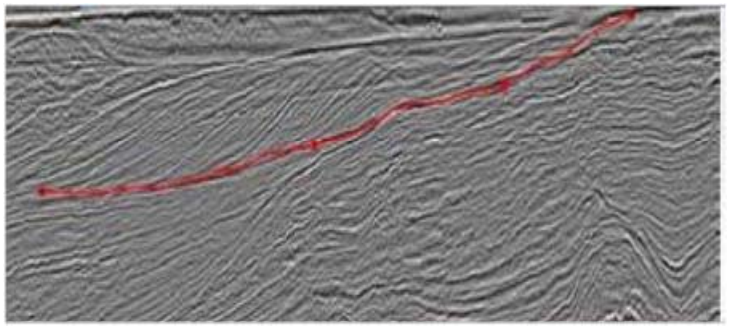
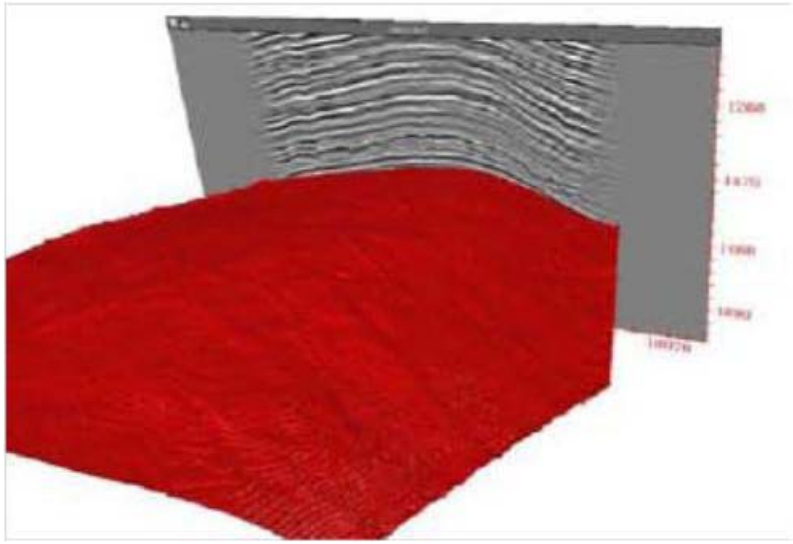
Seismic Imaging (6/6) - Interpretation

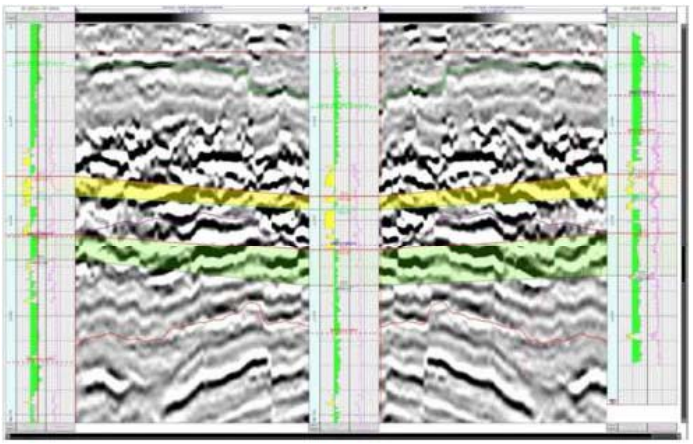
- **“pick the interface”**
- **Identify the <u>structure</u> “Trap” can trap oil/gas.**
  *Still need to validate the condition of petroleum system is right for oil/gas***.**
- **Many commercial apps available.**
  Total’s in-house tool “Sismage”



2D “picking”



3D “picking”



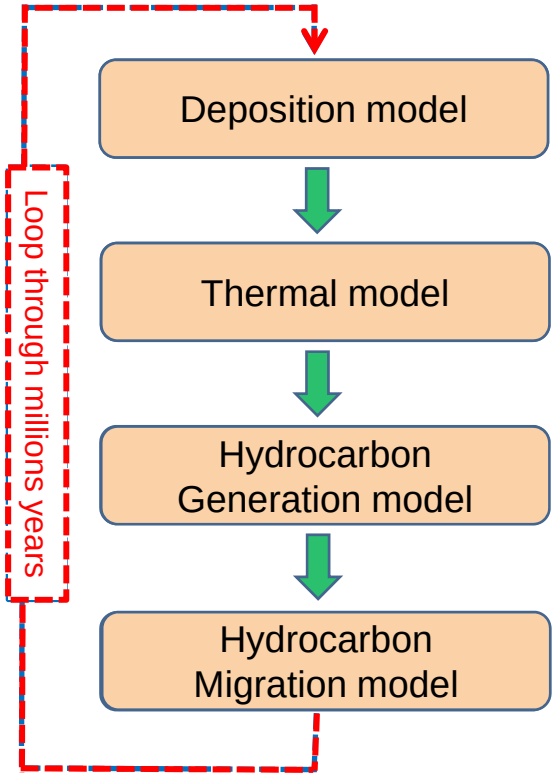
Correlated with Well logs

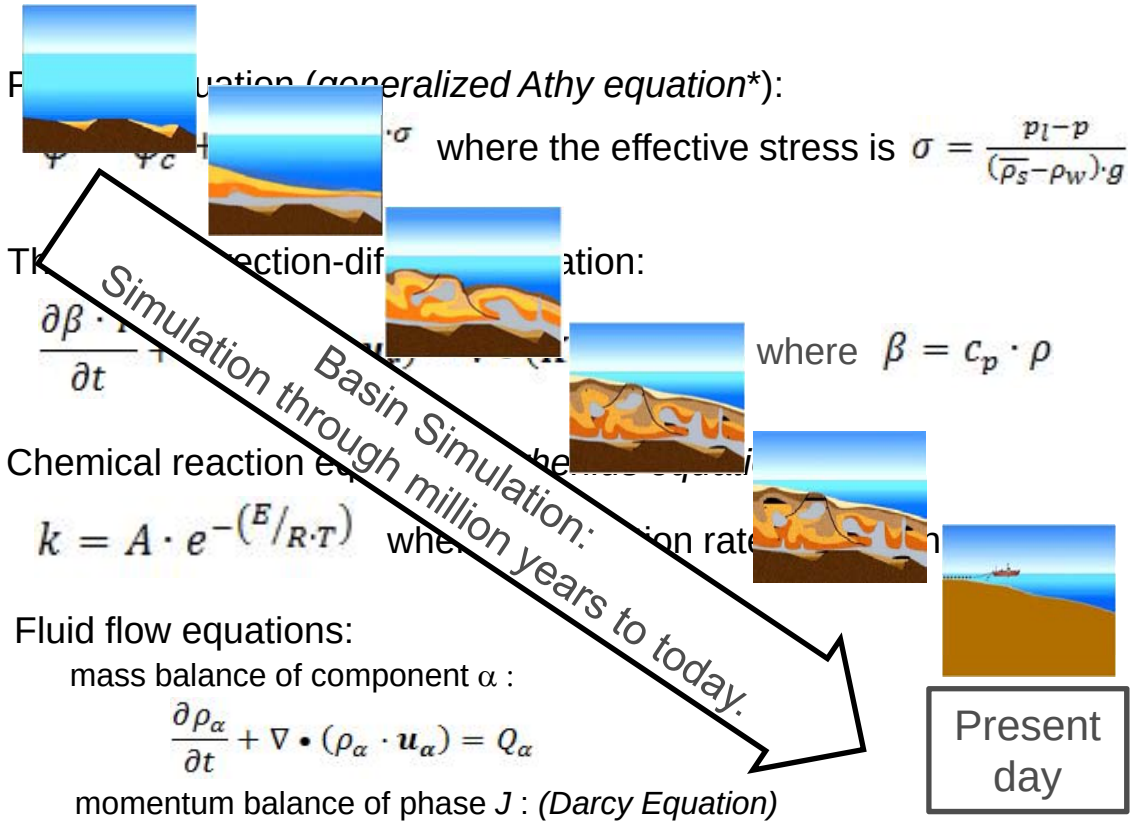
Basin Simulation (1/2)

What is Basin Simulation?

"… incorporates complex mathematical algorithms … to look at the dynamics of petroleum accumulations from millions of years in the past to the present day. … provides a better understanding of the risks and rewards in exploration…." - *Mobil Oil Corp. 1998 annual report (1998).*

How does it work?





F… uation (*generalized Athy equation**):

φ … φ_c + … $\cdot\sigma$ where the effective stress is $\sigma = \frac{p_l - p}{(\overline{\rho_s} - \rho_w)\cdot g}$

Th… ection-dif… ation:

$\frac{\partial \beta \cdot}{\partial t}$ + … where $\beta = c_p \cdot \rho$

Chemical reaction e… he…

$k = A \cdot e^{-(E/R\cdot T)}$ whe… ion rate…

Fluid flow equations:

mass balance of component α :

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \bullet (\rho_\alpha \cdot \boldsymbol{u}_\alpha) = Q_\alpha$$

momentum balance of phase *J* : *(Darcy Equation)*

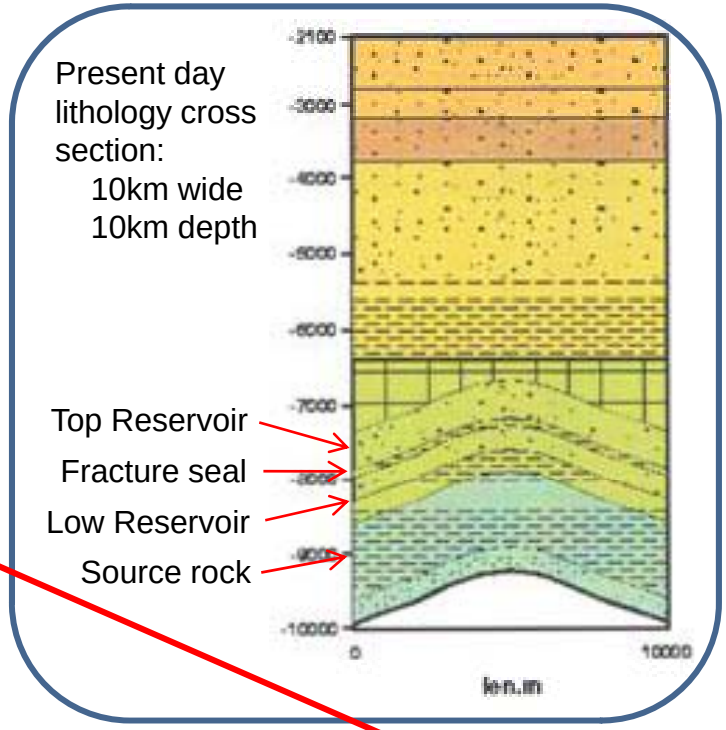
$$\varphi \cdot S_J \cdot (\boldsymbol{u}_J - \boldsymbol{u}_r) = -\frac{\boldsymbol{K} \cdot k_{r,J}}{\mu_J} \cdot \nabla(p_J - \rho_J \cdot g \cdot z)$$

*L.F. Athy, 1930, *Density, porosity and compaction of sedimentary rocks*, Bull. Amer. Assoc. Petrol. Geol. v. 14, pp. 1-24.
**John M. Hunt, 1995, *Petroleum Geochemistry and Geology*, Second Edition, Freeman

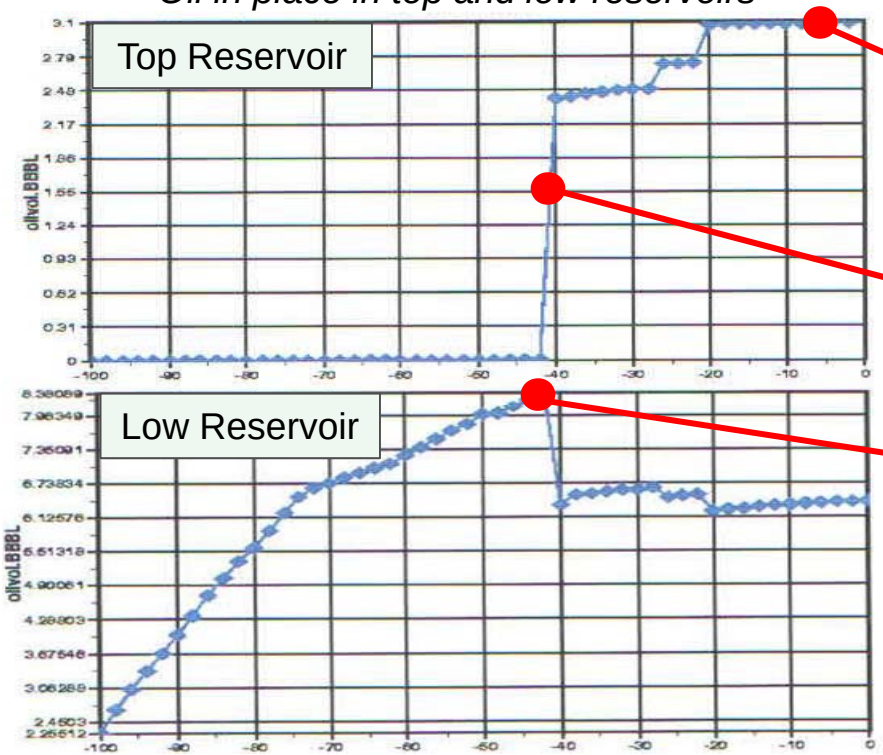
Basin Simulation (2/2) – *An Example*

Tale of Two Reservoirs with same type of Oil

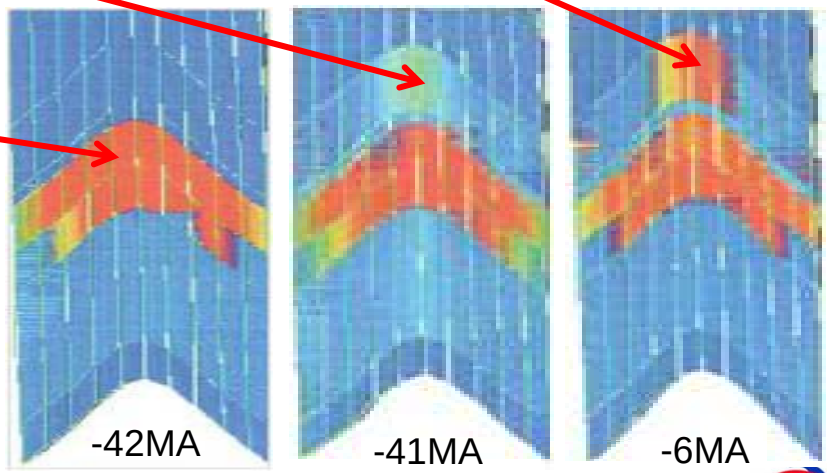
– *using basin simulation to simulate a fracture seal for low reservoir periodically opens up due to pressure build up and leak oil to fill up the top reservoir.*



Oil in place in top and low reservoirs



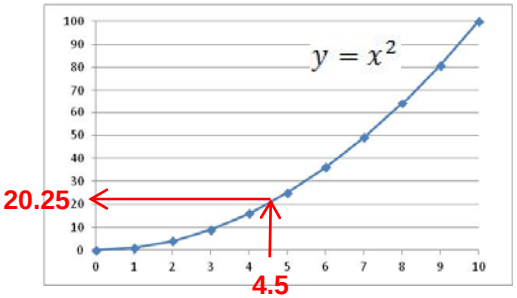
MA (-100 to 0)

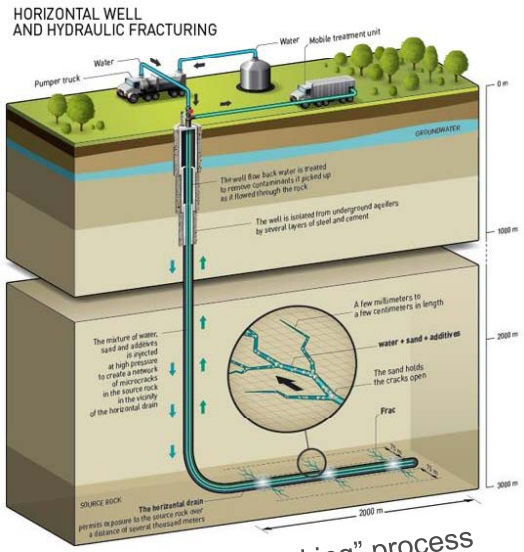


HPC to help to run many scenarios.

Engineering Applications – drilling and subsurface

- **Collection of "small" engineering applications as "Engineering Calculator"**
- **One method been used for a long time is: Type curve analysis**
  - Type curves are in the form of tables and plots.
  - Example:

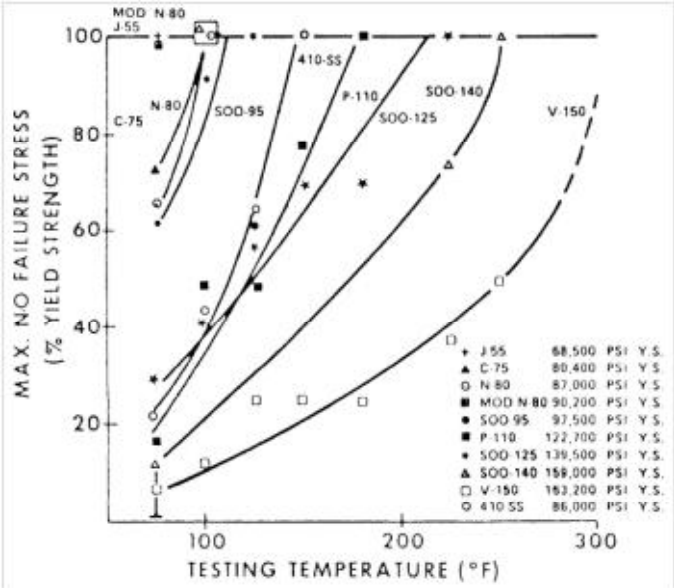




Shale gas "fracking" process

- **Type curve can be generated by Lab measurement.** ***Can also be generated by simulation results that take long time to run on current HPC system.***
- **"pHPC" is a type curve generated by many HPC runs. Engineers use it to get approximated value immediately without taking the long simulation run.**

Can "true" HPC replace pHPC?



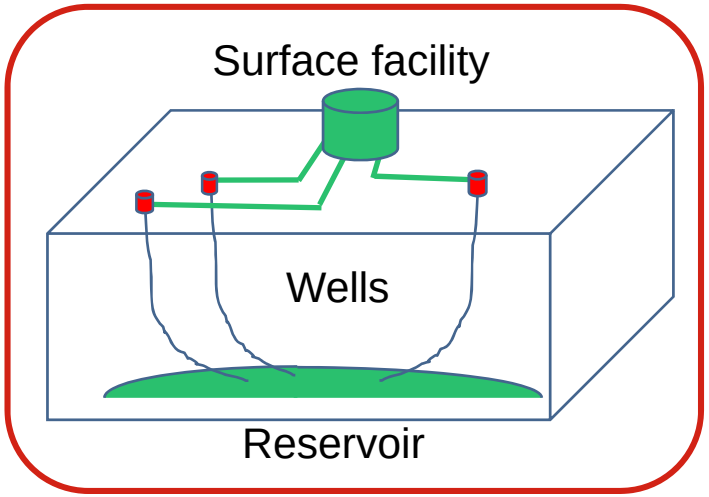
Type curve on steel strength under H_2S

Reservoir Simulation (1/3)

- **Reservoir Simulation is used for**
  - Estimate the reserve - *How much oil do you have?*
  - Manage field development – *where to drill wells*
  - Manage reservoir production – *how to produce, from where, how fast?*

- **Reservoir Simulation usually consists two parts:**
  - Fluid flow model *(Darcy Equation)* in the reservoir coupled with Well model
  - Facility Network model on the surface

- **Reservoir Simulation software:**
  - Commercial
    - "Nexus" from Halliburton
    - "Intersect" from Schlumberger
  - In-house proprietary
    - "EMpower" from ExxonMobil
    - "GigaPOWERS" from Saudi Aramco



A "too-simple" field

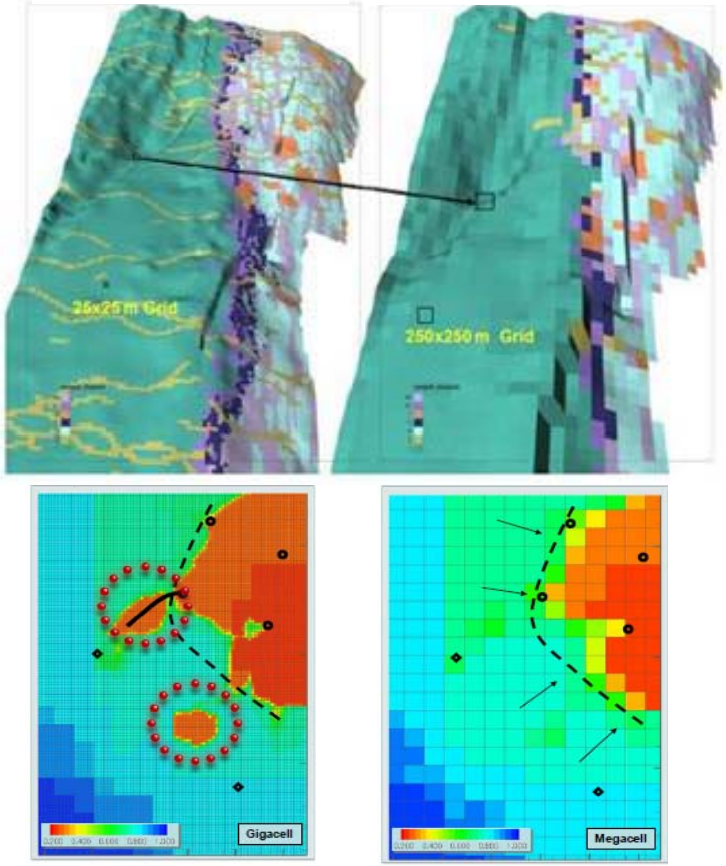
Reservoir Simulation (2/3) – *An Example*

The power of Giga-Cell

– An example from Saudi Aramco's GigaPOWERS simulator.

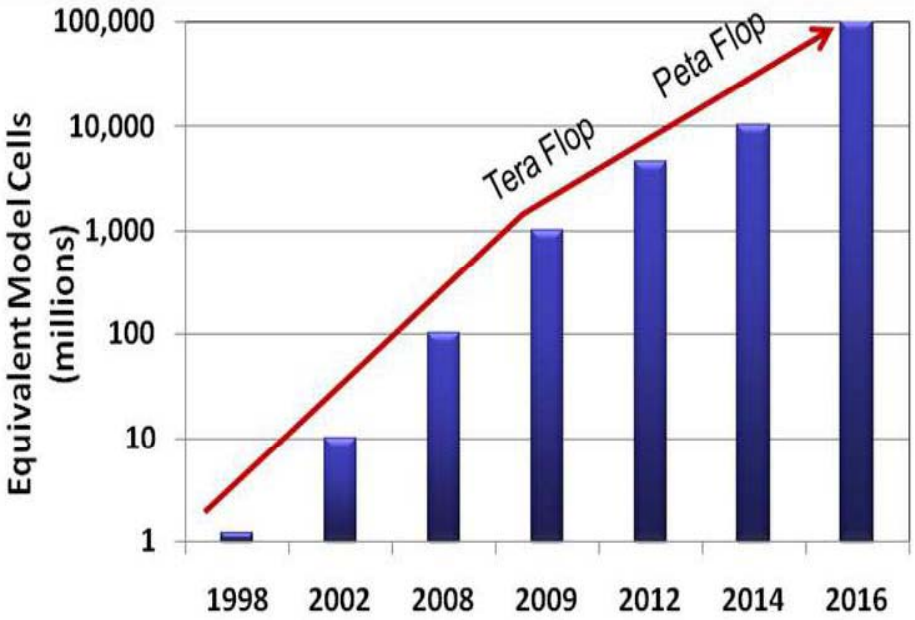
Real World Example of Upscaling

Geological Model	Upscaled Model
1B cell 25x25m	10M cell 250x250m



Model Growth

Model Size ~ Computational Speed (Flops)/1000



HPC enables solving problem in geological (seismic) scale!

From "Giga-Cell Simulation, Visualization and Real-Time Reservoir Monitoring", Ali Dogru, Saudi Aramco, Sep, 2010, World Oil Webcast".

Reservoir Simulation (3/3)

Some Remarks:

- **Linear solver – Multi-grid solver is good *but *NOT* parallel friendly.***
- **Optimization – need to optimize the production, for example, 700 wells + facility network. Optimization is *also *NOT* parallel friendly.***
- **Need to solve with rock machines - for example, how fast can I produce without smashing the well.**
  - One method currently been used is coupling reservoir simulation *NOT* with full FEM rock machines simulator, but by introducing the rock machines effect via "pHPC" Type curve approach.
- **Visualization of the input and the result?**
- **Grid resolution is limited by what seismic can provide.**

  Maybe the compute character of reservoir simulation will become "HTpC".

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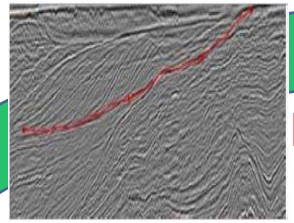
What are Oil & Gas Upstream Scientific Applications?

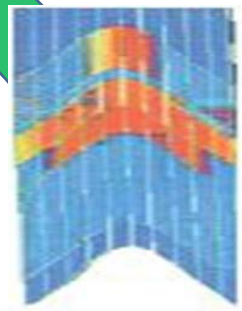
Recap. with the progress of HPC...

Seismic



Better image the earth

Basin



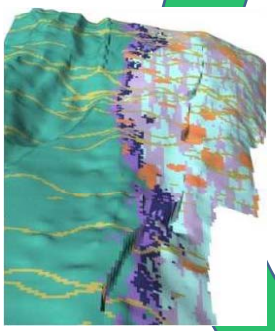
Improve the understanding of basin and petroleum system

HPC has brought these applications much closer.

Bring real time compute to engineering problem

Engineering

Solve in seismic scale and integrate with engineering applications



Reservoir

HPC Challenges *(Solutions anyone?)*

- **In Exascale system, No *"tHPC"* anymore but *"HTpC"* instead?**
- **Green problem *– How green it can be? Power? Garbage Data collection?***
- **Fault tolerance *– Hardware? Software?***
- **Programming languages**
- **IO and visualization *– both initial model and results***
- **People**
- **How about those small systems?**
- **And many more ……..**

HPC Challenges – *In search of Exascale….*

- **Some possible hardware solutions:**
  - multi-core solutions
    - BG/Q – 18 cores – 16 compute/1 OS/1 extra
    - SOC/NOC/memory integrated compute unit
    - *Question –*
      multi-level connections- what is the programming model?
  - Accelerating technology:
    - FPGA, GPU, MIC, …..
    - *Question –*
      what is the Host-Accelerator relation?
      what is the programming model?
  - Vector technology?

- **Programming directions:**
  - Low level programming language
  - Libraries/API
  - Domain Specific Language
  - High level programming language

2 main research directions: programming and hardware configuration

Derived from Henri Calandra "*Seismic processing challenges and computational road map" 2008*

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What are we doing in HPC Research?

- **Algorithm**
  - New algorithms for seismic imaging
- **Languages and Tools**
  - HMPP-GPU programming with CAPS
  - CoArray Fortran/PGAS Language with University of Houston
  - Task programming
  - Evaluating
    - o OpenACC for GPU
    - o Auto-tune MPI - ADCL: Abstract Data and Communication Library
- **Future Architectures**
  - Ultra low power compute - FPGA / GPU / MIC / ARM
- **Architecture matching**
  - Performance tuning / hardware evaluation
- **MISC**
  - Hierarchy IO
    - o Hardware – SSD, RAM
    - o Software – LSIO – Large Scale IO

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CoArray Fortran Project: (1/3)

- **Work with Prof. Barbara Chapman, University of Houston, since 2009.**

- **UHCAF is**
  - In-line with CAF in Fortran 2008 language specification
  - ***FREE*** and is available @ www2.cs.uh.edu/~openuh/download/
  - very easy to install
  - "mature" enough for TOTAL to try on RTM implementation

- **One of key features missing now is Parallel IO**
  - Maybe need to rethink what is IO - *file is not nature for scientific computing*
  - Maybe need to cast the problem within the programming
  - Maybe PGAS/GA can be "IO"

- **Code example and benchmark result**

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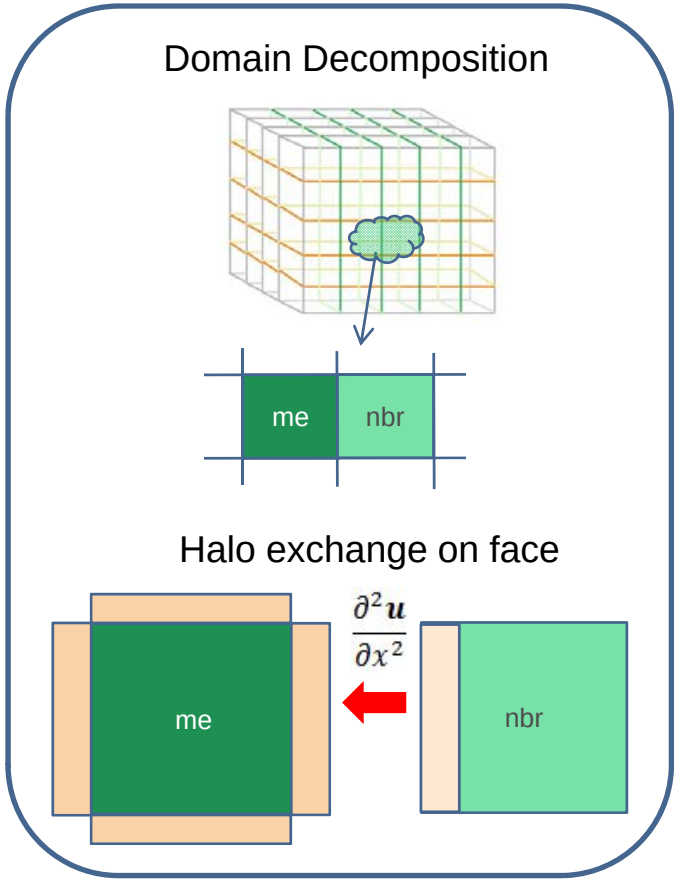
CoArray Fortran Project: (2/3)

Example: Halo exchange on 6 faces. MPI vs CAF

MPI - using MPI_ISEND and MPI_IRECV

```
count = lx*(jp-jm+1)*(kp-km+1)
if (rank_R .ne. MPI_PROC_NULL) then !-- right
  neighbor_R_s=u(ip-lx+1:ip,jm:jp,km:kp)
  call MPI_ISEND(neighbor_R_s,count,MPI_REAL,rank_R,tag,comm_cart,request(1),ierr)
  call MPI_IRECV(neighbor_R_r,count,MPI_REAL,rank_R,tag,comm_cart,request(2),ierr)
endif
if (rank_L .ne. MPI_PROC_NULL) then  !-- left
  neighbor_L_s=u(im:im+lx-1,jm:jp,km:kp)
  call MPI_ISEND(neighbor_L_s,count,MPI_REAL,rank_L,tag,comm_cart,request(3),ierr)
  call MPI_IRECV(neighbor_L_r,count,MPI_REAL,rank_L,tag,comm_cart,request(4),ierr)
end if
count = ly*(ip-im+1)*(kp-km+1)
if (rank_F .ne. MPI_PROC_NULL) then !--front
  neighbor_F_s=u(im:ip,jm:jm+ly-1,km:kp)
  call MPI_ISEND(neighbor_F_s,count,MPI_REAL,rank_F,tag,comm_cart,request(5),ierr)
  call MPI_IRECV(neighbor_F_r,count,MPI_REAL,rank_F,tag,comm_cart,request(6),ierr)
endif
if (rank_Bck .ne. MPI_PROC_NULL) then !--back
   neighbor_Bck_s=u(im:ip,jp-ly+1:jp,km:kp)
   call MPI_ISEND(neighbor_Bck_s,count,MPI_REAL,rank_Bck,tag,comm_cart,request(7),ierr)
   call MPI_IRECV(neighbor_Bck_r,count,MPI_REAL,rank_Bck,tag,comm_cart,request(8),ierr)
end if
count = lz*(ip-im+1)*(jp-jm+1)
if (rank_T .ne. MPI_PROC_NULL) then  !--top
   neighbor_T_s=u(im:ip,jm:jp,kp-lz+1:kp)
   call MPI_ISEND(neighbor_T_s,count,MPI_REAL,rank_T,tag,comm_cart,request(9),ierr)
   call MPI_IRECV(neighbor_T_r,count,MPI_REAL,rank_T,tag,comm_cart,request(10),ierr)
endif
if (rank_Btm .ne. MPI_PROC_NULL) then  !--bottom
   neighbor_Btm_s=u(im:ip,jm:jp,km:km+lz-1)
   call MPI_ISEND(neighbor_Btm_s,count,MPI_REAL,rank_Btm,tag,comm_cart,request(11),ierr)
   call MPI_IRECV(neighbor_Btm_r,count,MPI_REAL,rank_Btm,tag,comm_cart,request(12),ierr)
end if
call MPI_WAITALL(req_count,request,status,ierr)
```



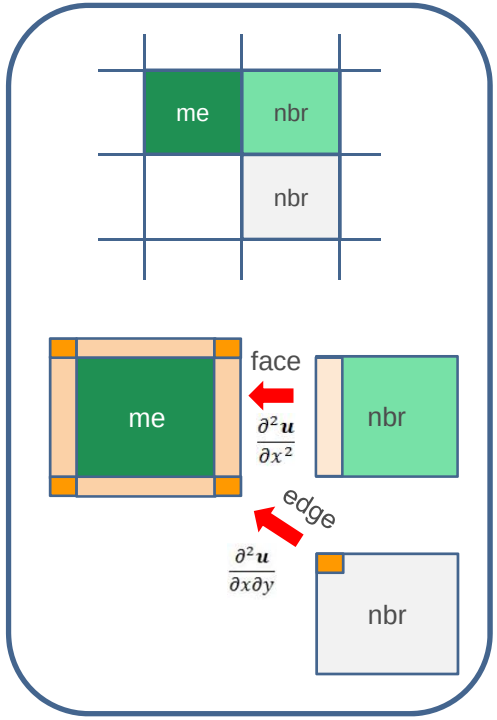
CAF

```
if( nbr(1) ) u(im-lx:im-1,jm:jp,km:kp)=u(ip-lx+1:ip,  jm:jp,km:kp)[px-1,py,pz]
if( nbr(2) ) u(ip+1:ip+lx,jm:jp,km:kp)=u(im:im+lx-1,jm:jp,km:kp)[px+1,py,pz]
if( nbr(3) ) u(im:ip,jm-ly:jm-1,km:kp)=u(im:ip, jp-ly+1:jp,km:kp)[px,py-1,pz]
if( nbr(4) ) u(im:ip,jp+1:jp+ly,km:kp)=u(im:ip,jm:jm+ly-1,km:kp)[px,py+1,pz]
if( nbr(5) ) u(im:ip,jm:jp ,km-lz:km-1)=u(im:ip,jm:jp,kp-lz+1:kp)[px,py,pz-1]
if( nbr(6) ) u(im:ip,jm:jp,kp+1:kp+lz)=u(im:ip,jm:jp,km:km+lz-1)[px,py,pz+1]
```

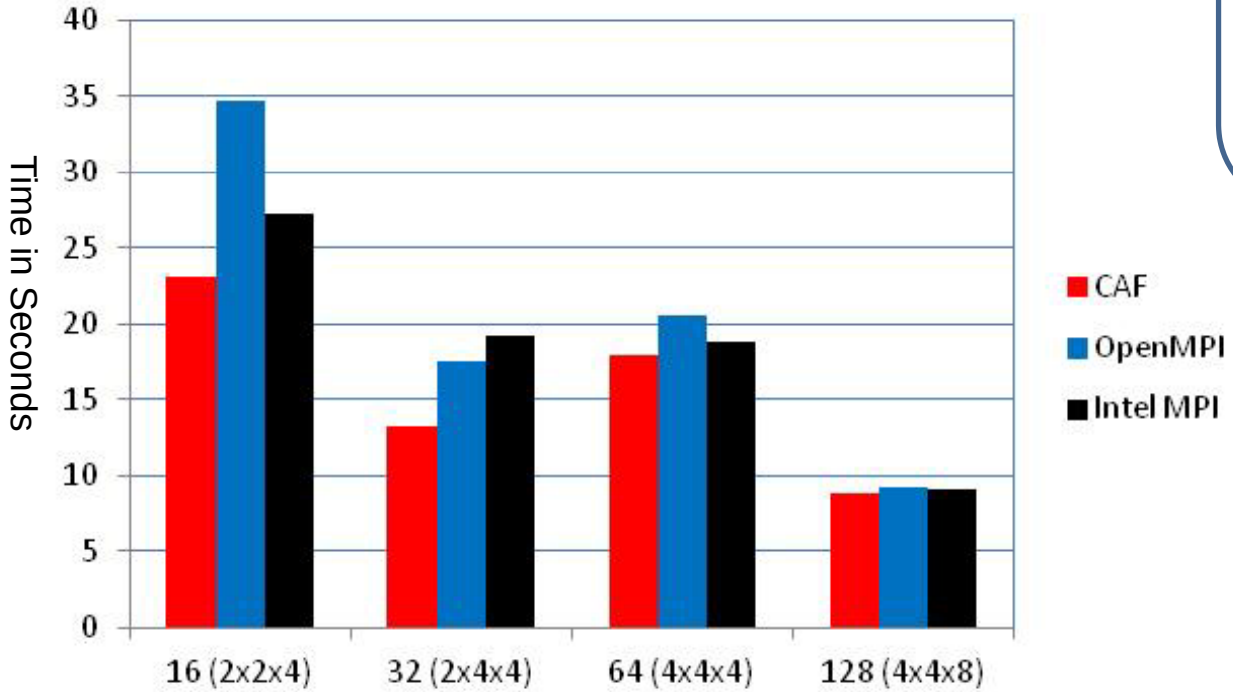
CoArray Fortran Project: (3/3)

Performance Result - Example:

- Problem size : 1024 x 2048 x 2048 with halo width : 4
- Halo exchanges on faces, i.e. $\frac{\partial^2 u}{\partial x^2}$ and edges, i.e. $\frac{\partial^2 u}{\partial x \partial y}$
- UHCAF on GASNET with non-contiguous data transfer



halo exchange time : UHCAF vs OpenMPI vs Intel MPI



processes(images) one process per node

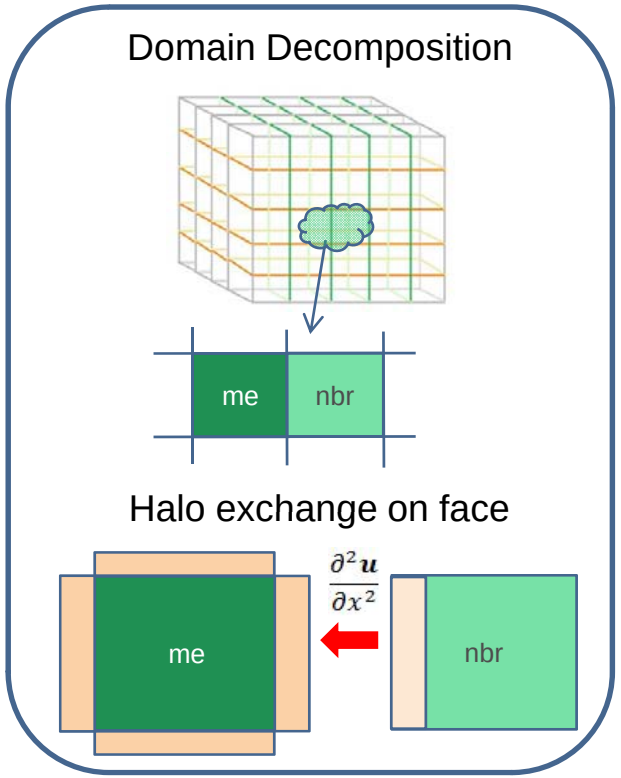
(on a cluster with Intel Nehalem 2.8GHz / QDR IB / fat tree)

ADCL: Abstract Data and Communication Library

- MPI code using ADCL to auto-select the “best” MPI method
- From Prof. Edgar Gabriel, University of Houston
- http://pstl.cs.uh.edu/projects/adcl.shtml

MPI - Halo exchange on 6 faces

```
count = lx*(jp-jm+1)*(kp-km+1)
if (rank_R .ne. MPI_PROC_NULL) then !-- right
  neighbor_R_s=u(ip-lx+1:ip,jm:jp,km:kp)
  call MPI_ISEND(neighbor_R_s,count,MPI_REAL,rank_R,tag,comm_cart,request(1),ierr)
  call MPI_IRECV(neighbor_R_r,count,MPI_REAL,rank_R,tag,comm_cart,request(2),ierr)
endif
if (rank_L .ne. MPI_PROC_NULL) then  !-- left
  neighbor_L_s=u(im:im+lx-1,jm:jp,km:kp)
  call MPI_ISEND(neighbor_L_s,count,MPI_REAL,rank_L,tag,comm_cart,request(3),ierr)
  call MPI_IRECV(neighbor_L_r,count,MPI_REAL,rank_L,tag,comm_cart,request(4),ierr)
end if
count = ly*(ip-im+1)*(kp-km+1)
if (rank_F .ne. MPI_PROC_NULL) then !--front
  neighbor_F_s=u(im:ip,jm:jm+ly-1,km:kp)
  call MPI_ISEND(neighbor_F_s,count,MPI_REAL,rank_F,tag,comm_cart,request(5),ierr)
  call MPI_IRECV(neighbor_F_r,count,MPI_REAL,rank_F,tag,comm_cart,request(6),ierr)
endif
if (rank_Bck .ne. MPI_PROC_NULL) then !--back
   neighbor_Bck_s=u(im:ip,jp-ly+1:jp,km:kp)
   call MPI_ISEND(neighbor_Bck_s,count,MPI_REAL,rank_Bck,tag,comm_cart,request(7),ierr)
   call MPI_IRECV(neighbor_Bck_r,count,MPI_REAL,rank_Bck,tag,comm_cart,request(8),ierr)
end if
count = lz*(ip-im+1)*(jp-jm+1)
if (rank_T .ne. MPI_PROC_NULL) then  !--top
   neighbor_T_s=u(im:ip,jm:jp,kp-lz+1:kp)
   call MPI_ISEND(neighbor_T_s,count,MPI_REAL,rank_T,tag,comm_cart,request(9),ierr)
   call MPI_IRECV(neighbor_T_r,count,MPI_REAL,rank_T,tag,comm_cart,request(10),ierr)
endif
if (rank_Btm .ne. MPI_PROC_NULL) then  !--bottom
   neighbor_Btm_s=u(im:ip,jm:jp,km:km+lz-1)
   call MPI_ISEND(neighbor_Btm_s,count,MPI_REAL,rank_Btm,tag,comm_cart,request(11),ierr)
   call MPI_IRECV(neighbor_Btm_r,count,MPI_REAL,rank_Btm,tag,comm_cart,request(12),ierr)
end if
call MPI_WAITALL(req_count,request,status,ierr)
```



ADCL*

Prepare the halo exchange size and topology

```
! - Specify the data structures
call ADCL_Vmap_halo_allocate(hwidth,vmapu,ierr)
call ADCL_Vector_register_generic( 3, vdims, 0, vmapu, MPI_REAL, u, vec_u, ierr)
! - Create  Topology
call ADCL_Topology_create(comm_cart, topo, ierr)
! -Create  Request
call ADCL_Request_create(vecu, topo, ADCL_FNCTSET_NEIGHBORHOOD, &
     request_u, ierr);
```

Halo exchange

```
call ADCL_Request_start(  request_u,  ierr);
```

*Thanks my colleagues, H. Haberdar and S. Feki for ADCL code.

Hierarchy IO – Software Approach

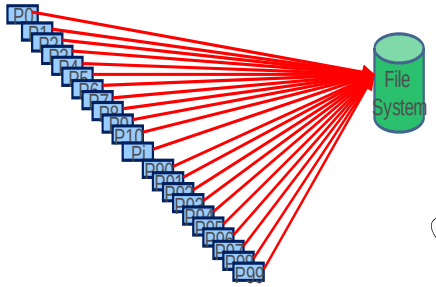
- Motivation:

  How to handle the increasing extreme large data flow (I/O)?

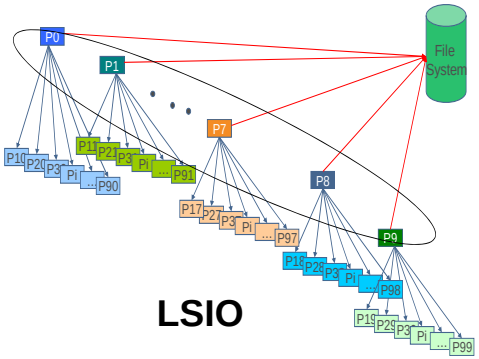
- Solutions:

  LSIO – “Large Scale IO” - to test the concept of using “agents” to handle the IO.

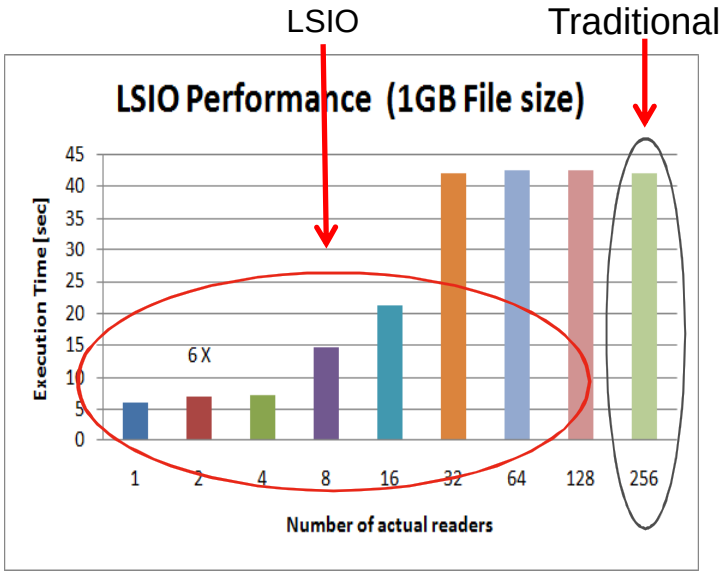
  This is a very simple concept and is NOT new.



Traditional



LSIO



Single 1GB file with 256 readers

(on a cluster with QDR IB, fat tree, Lustre PFS)

What if – What do I see the future of HPC in E&P?

Large Systems

Large System becomes even powerful….
2018 first Exascale system.

And then, the CLOUD is coming

E&P Information flows

Information Driven Computing

Cloud Computing: Microsoft, Amazon, Google, Private etc

How about the small ones?

E&P Information flows

Powerful Laptop:
(Intel i7 with 1.2TF SP GPU inside, 2010)

Powerful Tablet:
As powerful as laptop
(Intel i5 CPU, 2011)

Hardware will be there, but will need Software and <u>Expertise</u> to make this happen.

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Thank you very much

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