Large Scale Parallel Reservoir Simulations on a Linux PC-Cluster

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Saudi Aramco

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Outline

- Reservoir simulations at Saudi Aramco
- Formulation of the simulator (POWERS)
- PC - Clusters
- Implementation of the simulator on PC-Cluster
- Results
- Conclusions
Seismic Interpretation

Core Analysis & well logs

Well Production & Injection Data

Geological Model

Simulation Model
Demands for large scale reservoir simulations at Saudi Aramco is rapidly increasing.

- to reduce simulation turn around times
- to resolve heterogeneity in reservoirs
- to couple reservoir and facility simulations
- for well location and trajectory planning
Other potential benefits of large scale reservoir simulations to Saudi Aramco

- Longer time simulations
- Possibility of automatic or semi-automatic history matching
- Computational steering
- Exploitations of technological advances in computing
- .............
Growth of POWERS million+ cell simulation models

- 2000: 4 models
- 2001: 11 models
- 2002: 19 models
- 2003: 33 models
- 2004: 39 models
- 2005: 44 models
- 2006: 51 models

Number of Models

Projected computing capacity required for reservoir simulations

![Bar chart showing normalized compute capacity from 2000 to 2006]

- 2000: 1
- 2001: 2
- 2002: 3
- 2003: 15
- 2004: 19
- 2005: 21
- 2006: 23
Projected storage capacity required for reservoir Simulations

Normalized Storage Capacity

- 2000: 1
- 2001: 3
- 2002: 5
- 2003: 13
- 2004: 16
- 2005: 18
- 2006: 21
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Parallel Oil WatER Simulator

- It is a parallel reservoir simulator
- Functionality includes:
  - Black-Oil
  - Compositional
  - Dual Porosity Dual Permeability
  - Local Grid Refinement
  - Comprehensive Well Managements
Governing Equations:

\[
\frac{\partial (\phi \rho_a S_a)}{\partial t} + \nabla \cdot U_a = q
\]

\[
U_a = -\frac{K_a S_a K}{\mu_a} \rho_a (\nabla P_a - \rho_a g \nabla H)
\]

\[
\sum S_a = 1
\]
Numerical algorithm

- Implicit Formulation
- Newton-Raphson for nonlinearity
- Generalized Conjugate Residual to solve linearized equations
- Red-Black ordering
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PC-Cluster
Performance of different processors using the SPECfp2000 benchmark

![Bar chart showing the SPECfp2000 benchmark results for different processors.](chart)

- Power 3-375 MHz IBM-NH-2: 322
- SGI MIPS-Pro 500 MHz-R14K: 532
- Power 4-1 GHz IBM-Reggata: 843
- Pentium IV 2.4 GHz: 872
## Bandwidth and Latency of various switches in PC-Clusters configurations

<table>
<thead>
<tr>
<th>Switch</th>
<th>Bandwidth (Mbytes/sec)</th>
<th>Latency (microsecond)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Ethernet</td>
<td>12</td>
<td>150</td>
</tr>
<tr>
<td>Gigabit</td>
<td>128</td>
<td>26-12</td>
</tr>
<tr>
<td>Myrinet</td>
<td>421</td>
<td>7</td>
</tr>
<tr>
<td>Quadrics</td>
<td>400</td>
<td>5</td>
</tr>
</tbody>
</table>
Number of installation of NOW Clusters in the Top500 supercomputers list

- Intel
- HP
- Alpha
- AMD
Status of PC-Cluster Computations at Saudi Aramco

- Seismic processing activities in Saudi Aramco are taking full advantages of PC-cluster technology and abandoned other systems.
- Reservoir simulation models are now being migrated to PC-Cluster platform (this study).
Quadrics Cluster (Cluster_Q)

<table>
<thead>
<tr>
<th>Configuration of the Quadrics Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nodes</strong></td>
</tr>
<tr>
<td><strong>Processors (CPUs)</strong></td>
</tr>
<tr>
<td><strong>Clock</strong></td>
</tr>
<tr>
<td><strong>Total RAM</strong></td>
</tr>
</tbody>
</table>
Quadrics Cluster (Cluster_Q)

<table>
<thead>
<tr>
<th>Software on Quadrics Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OS</strong></td>
</tr>
<tr>
<td><strong>Compiler</strong></td>
</tr>
<tr>
<td><strong>Debugger</strong></td>
</tr>
<tr>
<td><strong>Communication</strong></td>
</tr>
<tr>
<td><strong>Job submission</strong></td>
</tr>
<tr>
<td><strong>Optimization Tools</strong></td>
</tr>
</tbody>
</table>
Quadrics Cluster (Cluster_Q)
# Myrinet Cluster (Cluster\_M)

## Configuration of Myrinet Cluster

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Clusters</td>
<td>2</td>
</tr>
<tr>
<td>Nodes</td>
<td>256</td>
</tr>
<tr>
<td>Processors (CPUs)</td>
<td>512 (Xeon)</td>
</tr>
<tr>
<td>Clock</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Total RAM</td>
<td>1024 GB (1 TB)</td>
</tr>
<tr>
<td>External Storage</td>
<td>20 TB</td>
</tr>
</tbody>
</table>
# Myrinet Cluster (Cluster_M)

<table>
<thead>
<tr>
<th>Software</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>Redhat Linux 7.3</td>
</tr>
<tr>
<td>Compiler</td>
<td>Intel ifc (v.7), ifc</td>
</tr>
<tr>
<td>Debugger</td>
<td>Totalview</td>
</tr>
<tr>
<td>Communication</td>
<td>MPICH - Myrinet</td>
</tr>
<tr>
<td>Job submission</td>
<td>PBS</td>
</tr>
<tr>
<td>Optimization Tools</td>
<td>Vampir, VampirTrace, Vtune</td>
</tr>
</tbody>
</table>
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Parallel Implementations of POWERS

- POWERS was originally written in Connection Machine Fortran.
- Code was later ported to IBM SP using OpenMP and MPI calls.
- No modification of the numerical algorithm was made in this or in the previous port.
Summary of PC-Cluster porting activities

- Recompiled the code on cluster using the Intel-ifc compiler
- Expanded MPI parallelization into a second dimension
- Benchmarked interconnect switches (Mericom-Myrinet and Quadrics-Elan) using code kernels and the full code
- Revised MPI communication algorithms in the code
- Tuned performance
**Original Implementation**

**J-Dimension**

- CPU 0
- Threads
- CPU m

**I-Dimension**

- Node 0
- MPI
- Node 1
- Node n
Porting from IBM NH2 to PC - Cluster
New Implementation

Node 0
CPU 0
CPU 1
OpenMP Threads

Node m
CPU 0
CPU 1

MPI-Communication

J-Dimension

Grid Partitioning

I-Dimension

J-Dimension

I-Dimension
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## Test Cases

<table>
<thead>
<tr>
<th>Model</th>
<th>Grid Size (million cells)</th>
<th>Number of wells</th>
<th>Years Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>3.7</td>
<td>144</td>
<td>3</td>
</tr>
<tr>
<td>Model II</td>
<td>9.6</td>
<td>2,960</td>
<td>50</td>
</tr>
<tr>
<td>Model III</td>
<td>0.2</td>
<td>4,000</td>
<td>62</td>
</tr>
<tr>
<td>Model IV</td>
<td>0.5</td>
<td>200</td>
<td>24</td>
</tr>
</tbody>
</table>
Model I Execution time on PC Clusters and IBM NH2

![Bar chart showing execution time on different clusters and IBM NH2.](chart.png)

- Cluster_Q
- Cluster_M
- IBM NH2

**Time (sec)**

- 16 CPU
- 32 CPU
A comparison of platforms

- IBM NH2
- IBM Regatta
- Cluster_Q
Execution time of Model I on PC Clusters

![Graph showing execution time vs number of processors for different clusters.](graph.png)
Model I Simulation time

Time (sec)

Number of Processors

- IBM NH2
- Cluster_M

0 1000 2000 3000 4000 5000 6000 7000 8000 9000

16 32 48 64 80 96 120
Scalability of Model I

Number of Processors vs Speed up

Ideal
NH2 (total)
NH2 (core)
Cluster (total)
Cluster (core)
Simulations of Model II

- IBM NH2: 24 hours
- PC Cluster: 6 hours

96 Processors
Simulations of Model II on Cluster _M

![Bar chart showing time (hr) vs. number of processors (64, 96, 125). The time decreases as the number of processors increases.]
Simulations of Model II on Cluster _M

![Graph showing speed up versus number of processors for ideal, actual, and computation models.](image-url)
Timing of Code Sections in Model I

![Graph showing the timing of code sections across different numbers of processors. The graph includes lines for communication (Comm), synchronization (Synch), core (Core), and total time. The x-axis represents the number of processors (16 to 120), and the y-axis represents time (in seconds) ranging from 0 to 3000 seconds.)
## Model III execution time

<table>
<thead>
<tr>
<th>CPU</th>
<th>Cluster_Q (sec.)</th>
<th>Cluster_M(orig) (sec.)</th>
<th>Cluster_M(opt) (sec.)</th>
<th>IBM NH2 (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56,100</td>
<td>45,830</td>
<td>45,830</td>
<td>98,350</td>
</tr>
<tr>
<td>10</td>
<td>9,900</td>
<td>7,350</td>
<td>7,090</td>
<td>13,500</td>
</tr>
<tr>
<td>20</td>
<td>8,000</td>
<td>5,700</td>
<td>4,860</td>
<td>7,700</td>
</tr>
<tr>
<td>50</td>
<td>---</td>
<td>5,230</td>
<td>3,720</td>
<td>4,675</td>
</tr>
</tbody>
</table>
Effect of optimized communication algorithm for Model I

Simulation

![Graph showing the effect of optimized communication algorithm for Model I. The graph plots the ratio of optimized (T_opt) to original (T_orig) time against the number of processors. The x-axis represents the number of processors (16, 32, 64, 96, 120), and the y-axis represents the ratio T_opt / T_orig. There are two lines: one for total time and another for core time. The total time line starts at around 1 and decreases as the number of processors increases, while the core time line starts at around 0.7 and decreases as the number of processors increases.]
Communication Overhead in Model III Simulation

Time (sec)

Number of Processors

Reg Comm (orig)
Reg Comm (opt)
Irreg Comm (orig)
Irreg Comm (opt)
Timing with Different Decompositions in Models I and IV

The graph shows the time (in seconds) taken for Blocking with different decompositions in Models I and IV. The x-axis represents different blocking configurations, and the y-axis represents time in seconds. The graph compares Model I total, Model I core, Model IV total, and Model IV core times for each blocking configuration.
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Based on our observations in this work, we conclude the followings:

- **PC-Clusters** are highly attractive option for parallel reservoir simulations in terms of performance and cost.

- Simulations of massive reservoir models (in the order of 10 million cells) are possible at affordable computing cost.

- Serial computation, synchronization and I/O issues become significant at high number of processors.
Conclusions

- Commodity switches can be effectively used in high performance computing platform for reservoir simulation.

- Both hardware and software tools such as compilers are constantly improving which in turn will reduce execution times and computing costs on PC-clusters.

- The computing hardware is continuously changing and we will follow up and monitor to take advantage of new and emerging technologies.