“PARTITIONING” IN MPI
FAULT TOLERANCE FOR MPI
COMMUNICATION AND NOISE AS HPC BOTTLENECK
DYNAMIC LOAD BALANCING

DISTRIBUTED OPERATING SYSTEMS, SCALABILITY, SS 2018

{THANKS TO AMNON BARAK, CARSTEN, MAKSYM, ALEX MARGOLIN, …}
Partitioning:
bulk synchronous execution
MPI collectives, Fault Handling

Communication and Noise

Load Balancing (MosiX):
migration mechanisms
information dissemination
decision making
- independent OS processes
- bulk synchronous execution (HPC)
  - sequence: compute - communicate
  - all processes wait for all other processes
- often: message passing
  for example Message Passing Library (MPI)
- all processes execute same program

- while (true)
  { work; exchange data (collective operation)}

- common in High Performance Computing: Message Passing Interface (MPI) library
DIVIDE AND CONQUER

node 1

CPU #1

result 1

problem

result 2

CPU #2

node 2

CPU #1

result 3

result 4

CPU #2
MPI: Message Passing Interface

- Library for message-oriented parallel programming
- Common but not mandatory

BS Programming model:
- Multiple instances of same program
- Independent calculation
- Communication, synchronization
MPI STARTUP & TEARDOWN

- MPI program is started on all processors
  - `MPI_Init()`, `MPI_Finalize()`
- Communicators (e.g., `MPI_COMM_WORLD`)
  - `MPI_Comm_size()`
  - `MPI_Comm_rank()`:
    "Rank" of process within this set
- Typed messages
- (Dynamically create and spread processes using `MPI_Spawn()` (since MPI-2))
MPI EXECUTION

- Communication
  - Point-to-point
  - Collectives
- Synchronization
  - Test
  - Wait
  - Barrier

```c
MPI_Send(
    void* buf,
    int count,
    MPI_Datatype,
    int dest,
    int tag,
    MPI_Comm comm
)

MPI_Recv(
    void* buf,
    int count,
    MPI_Datatype,
    int source,
    int tag,
    MPI_Comm comm,
    MPI_Status *status
)

MPI_Bcast(
    void* buffer,
    int count,
    MPI_Datatype,
    int root,
    MPI_Comm comm
)

MPI_Reduce(
    void* sendbuf,
    void *recvbuf,
    int count,
    MPI_Datatype,
    MPI_Op op,
    int root,
    MPI_Comm comm
)

MPI_Barrier(
    MPI_Comm comm
)

MPI_Test(
    MPI_Request* request,
    int *flag,
    MPI_Status *status
)

MPI_Wait(
    MPI_Request* request,
    MPI_Status *status
)
```
<table>
<thead>
<tr>
<th></th>
<th>blocking call</th>
<th>non-blocking call</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>synchronous</strong></td>
<td>returns when message has been delivered (i.e. received by some)</td>
<td>returns immediately, sender later checks for delivery (Test/Wait)</td>
</tr>
<tr>
<td>communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>asynchronous</strong></td>
<td>returns when send buffer can be reused</td>
<td>returns immediately, sender later checks for send buffer</td>
</tr>
<tr>
<td>communication</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

“buffer”: variable containing the message to be sent
int rank, total;
MPI_Init();
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &total);

MPI_Bcast(...);
/* work on own part, determined by rank */

if (id == 0) {
    for (int rr = 1; rr < total; ++rr)
        MPI_Recv(...);
    /* Generate final result */
} else {
    MPI_Send(...);
}
MPI_Finalize();
interpr**etation for parallel systems:**

- **P:** section that can be parallelized
- **1-P:** serial section
- **N:** number of CPUs

\[
\text{Speedup}(P,N) = \frac{1}{1 - P + \frac{P}{N}}
\]
AMDAHL’S LAW

Serial section:
communicate, longest sequential section

Parallel, “Serial”, possible speedup:

- 1ms, 100 μs: 1/0.1 → 10
- 1ms, 1 μs: 1/0.001 → 1000
- 10 μs, 1 μs: 0.01/0.001 → 10
- ...

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BLOCK SYNCHRONOUS EXECUTION

Communication

Computation

Communication
BLOCK SYNCHRONOUS EXECUTION

Communication

Computation

Communication
BLOCK SYNCHRONOUS EXECUTION

Communication

Computation

Communication
for(int t = 0; t < TIMESTEPS; t++) {
    /* ... Do work ... */

    SCR_Need_checkpoint(&flag);
    if (flag) {
        SCR_Start_checkpoint();
        SCR_Route_file(file, scr_file);
        /* save checkpoint into scr_file */
        SCR_Complete_checkpoint(1);
    }
}

...
MPI_Init();
SCR_Init();

if (SCR_Route_file(name, ckpt_file) == SCR_SUCCESS) {
    // Read checkpoint from ckpt_file
} else {
    // There is no existing checkpoint
    // Normal program startup
}
ULFM USER LEVEL FAULT MITIGATION

- **MPI_Comm_failure_ack**\( (\text{comm}) \)**
  - Resumes matching for MPI_ANY_SOURCE
- **MPI_Comm_failure_get_acked**\( (\text{comm}, \&\text{group}) \)**
  - Returns to the user the group of processes acknowledged to have failed

- **MPI_Comm_revoke**\( (\text{comm}) \)**
  - Non-collective collective, interrupts all operations on \text{comm} (future or active, at all ranks) by raising MPI_ERR_REVOKED

- **MPI_Comm_shrink**\( (\text{comm}, \&\text{newcomm}) \)**
  - Collective, creates a new communicator without failed processes (identical at all ranks)
- **MPI_Comm_agree**\( (\text{comm}, \&\text{mask}) \)**
  - Collective, agrees on the AND value on binary mask, ignoring failed processes (reliable AllReduce), and the return core
WEAK VS. STRONG SCALING

Strong:
- accelerate same problem size

Weak:
- extend to larger problem size
- noise
  - execution time jitter
  - interrupt latency
- balance load in case of unbalanced applications
THE NEED FOR BALANCING

work item

time

Barrier
THE NEED FOR BALANCING

work item

Barrier

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Use common sense to avoid:

- OS usually not directly on the critical path, BUT OS controls: interference via interrupts, caches, network, memory bus, (RTS techniques)
- avoid or encapsulate side activities
- small critical sections (if any)
- partition networks to isolate traffic of different applications (HW: Blue Gene)
- do not run Python scripts or printer daemons in parallel
- use small kernel to isolate
balancing in systems architecture

- application
- run-time library
- operating system
SCHEDULER: GLOBAL RUN QUEUE

Immediate approach: global run queue

all ready processes
SCHEDULER: GLOBAL RUN QUEUE

- ... does not scale
  - shared memory only
  - contended critical section
  - cache affinity
  - ...

- separate run queues with explicit movement of processes
High Performance Computing

- Operating System / Hardware: “All” participating CPUs: active / inactive
  - Partitioning (HW)
  - Gang Scheduling (OS)

- Within Gang/Partition: Applications balance !!!
HW PARTITIONS & ENTRY QUEUE

request queue

Application

BATCH SCHEDULER
PROPERTIES HW PARTITIONS

- optimizes usage of network
- takes OS off critical path (busy waiting)
- best for strong scaling
- burdens application/library with balancing
- potentially wastes resources
- current state of the art in High Performance Computing (HPC)
SPLITTING BIG JOBS

work item

time

overdecomposition & “oversubscription”
Execute small jobs in parallel (if possible)
Programming Model

- many (small) decoupled work items
- overdecompose
  create more work items than active units
- run some balancing algorithm

Example: CHARM ++
- create (many) more processes
- use OS information on run-time and system state to balance load
- examples:
  - run multiple applications
  - create more MPI processes than nodes (!)
added overhead

- additional communication between smaller work items (memory & cycles)
- more context switches
- OS on critical path (for example communication)
required:

- mechanism for migrating load
- information gathering
- decision algorithms

MosiX system as an example

-> Barak’s slides now
MOSIX is a unifying management layer

Applications

MOSIX - OS
Mostly user-level implementation

Continuous feedback about the state of resources

All the nodes run like one server with many cores
The main software components

1. Preemptive process migration
   • Can migrate a running processes anytime
   • Like a course-grain context switch
     • Implication on caching, scheduling, resource utilization

2. OS virtualization layer
   • Allows a migrated process to run in remote nodes

3. On-line algorithms
   • Attempt to optimize a given goal function by process migration
     • Match between required and available resources
     • Information dissemination – based on partial knowledge

Note: features that are taken for granted in shared-memory systems, are not easy to support in a cluster
The OS virtualization layer

• A software layer that allows a migrated process to run in remote nodes, away from its home node
  • All system-calls are intercepted
    • Site independent sys-calls are performed locally, others are sent home
  • Migrated processes run in a sandbox

• Outcome:
  • A migrated process seems to be running in its home node
  • The cluster seems to the user as one computer
  • Run-time environment of processes are preserved - no need to change or link applications with any library, copy files or login to remote nodes

• Drawback: increased (reasonable) communication overhead
Process migration - the home node model

- Process migration – move the process context to a remote node
- System context stay at “home” thus providing a single point of entry
- Process partition preserves the user’s run-time environment
- Users need not care where their process are running
**FORK IN MOSIX**

- Deputy
  - fork()
  - Establish a new link
  - Deputy\(_{child}\)
  - Reply from fork()

- Remote
  - Remote\(_{child}\)
  - Reply from fork()
  - fork() syscall request

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PROCESS MIGRATION IN MOSIX

**Process**
- Migration request
- Send state, memory maps, dirty pages
- Ack
- Transition
- Finalize migration
- Ack
- Migration completed

**migdaemon**
- Remote
- fork()

- Deputy

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Distributed bulletin board

• An n node cluster/Cloud system
  – Decentralized control
  – Nodes can fail at any time
• Each node maintains a data structure (vector) with an entry about selected (or all) the nodes
• Each entry contains:
  – State of the resources of the corresponding node, e.g. load
  – Age of the information (tune to the local clock)
• The vector is used by each node as a distributed bulletin board
  – Provides information about allocation of new processes
CENTRALIZED GLOBAL STATE
DECENTRALIZED GLOBAL STATE
GOSSIP
Node X

Node Y

GOSSIP
When

**M:** load difference discovered
anomaly discovered
anticipated

Where

**M:** memory, cycles, comm
consider topology
application knowledge

Which

**M:** past predicts future
application knowledge
Load balancing algorithms

• **When** - Load difference between a pair of nodes is above a threshold value
• **Which** - Oldest process (assumes past-repeat)
• **Where** - To the known node with the lowest load
• Many other heuristics

• **Performance**: our online algorithm is only \(~2\%\) slower than the optimal algorithm (which has complete information about all the processes)
Memory ushering

• **Heuristics:** initiate process migration from a node with no free memory to a node with available free memory

• **Useful:** when non-uniform memory usage (many users) or nodes with different memory sizes

• **Overrides load-balancing**

• **Recall:** placement problem is NP-hard
Memory ushering algorithm

- **When** - free memory drops below a threshold
- **Where** - the node with the lowest load, to avoid unnecessary follow-up migrations
- **Which** - smallest process that brings node under threshold
- **To reduce the communication overhead**
- memory
- cpu load
- IPC
SOME PRACTICAL PROBLEMS

- flooding
  all processes jump to one new empty node
  => decide immediately before migration commitment
  extra communication, piggy packed

- ping pong
  if thresholds are very close, processes moved back and forth
  => tell a little higher load than real
Scenario:
compare load on nodes 1 and 2
node 1 moves process to node 2

Solutions:
add one + little bit to load
average over time

Solves short peaks problem as well
(short cron processes)
- execution/communication time jitter matters (Amdahl)
- HPC approaches: partition ./ balance
- dynamic balance components: migration mechanism, information bulletin, decision: which, when, where