High-speed Checkpointing for High Availability

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Xen Summit 5, November 2007

High availability in a nutshell

- The ability to tolerate *fail-stop physical* failure
- *Not* software failures
- *Not* non-fatal errors (memory errors etc)
- *Not* cold-start (recovery should be seamless)

High availability is hard

- Customized hardware is expensive and inflexible
- Operating systems are complex and ever-changing
- Libraries are restrictive
- Applications infinitely reinvent the (square) wheel

The Xen solution

- Machine state is readily available
- Interface is narrow and stable
- Performance is good

The REMUS High Availability Service

Redundancy-
Enhanced
Moderately
Unreliable
Servers

A checkpoint-based service providing

- Generality
- Transparency
- Seamless failure recovery
- Multiprocessor support
- Active-Passive configuration

Outline

Introduction

Design and Implementation

- High-speed checkpointing
- Network buffering
- Disk replication
- Failure detection

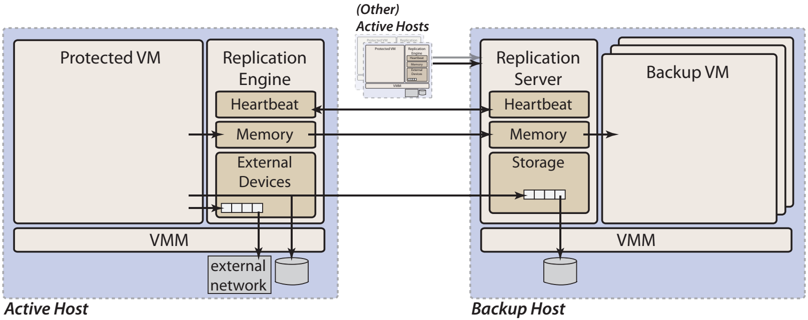
Evaluation

Conclusion

Approach

- Encapsulate execution in a virtual machine
- Perform frequent lightweight checkpoints
- Execute *speculatively* between checkpoints
- Propagate checkpoints asynchronously

High-level overview



General operation

- The primary and backup begin with identical disk images
- Attach disk and network proxies to the protected VM when it begins execution
- At frequent intervals ($\approx 25ms$) take a checkpoint of memory and disk state and propagate it to the backup
- When the checkpoint has been acknowledged at the backup, buffered output is released to external clients

Virtual machine checkpointing

- Modification of existing code supporting live migration
  - In essence, it moves the virtual machine to a new location, but also leaves it running at the old location
  - The remote node does not allow the image to execute until a failure occurs at the primary
- Required several changes
  - Performance optimizations
  - Changes to Xen to allow checkpointed images to resume execution (now in the upstream codebase)
  - Changes to ensure that a *consistent* image is available at all times on the backup

Live migration in a nutshell

- Xen puts the virtual machine into *shadow paging mode*
  - Guest page tables are replaced at the hardware level with versions in which all pages are marked read-only
  - Write faults allow Xen to maintain a map of dirty pages before restoring read-write access to pages (or propagating page faults)
- Live migration is performed by copying dirty pages to the new location without pausing the guest
- This occurs in rounds: the migration process chases the virtual machine
- A final round before migration pauses the domain in order to capture a consistent image of up-to-date state before activating the VM at the new location
- The original VM is destroyed

Checkpointing support

- Checkpointing is the repeated execution of the final stage of live migration: all state changed since the previous epoch is propagated
- To allow repeated checkpointing, new functions were added to Xen to mark a domain as runnable after suspend
- The migration process was converted into a persistent daemon
- The process receiving migration data was modified to buffer checkpoint rounds in memory and apply them only after they had been completely received
- It was also modified to loop waiting for new checkpoint data unless the connection to the sender times out

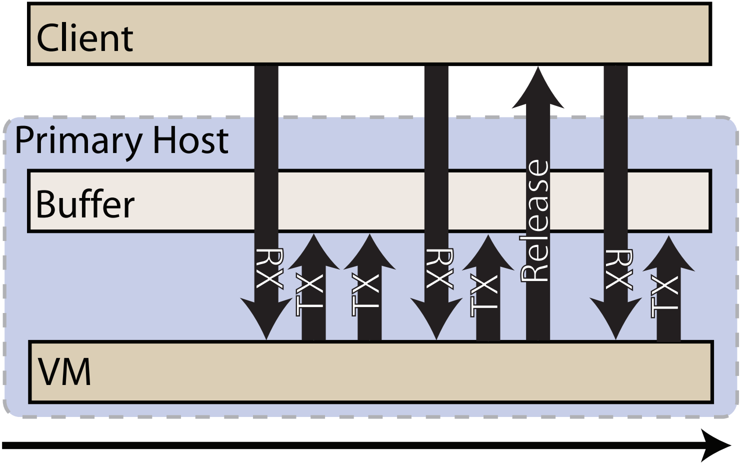
Performance optimizations

- Checkpoint data is buffered locally and propagated after the guest has resumed
- Special signalling is used to request guest suspension and receive notification upon completion
  - This reduces the time required for this operation from an average of 30-40ms (worst-case over 500ms) to roughly 100us
- The guest suspend process is simplified. Devices are no longer disconnected on suspend or reconnected on resume

Network buffer principles

- IP networks are unreliable
  - They may lose, duplicate or reorder packets
  - Applications either tolerate this or use a layer above IP to provide stream semantics (i.e. TCP)
- Replication does not need to preserve network data to ensure correctness
  - If network output is lost due to failover, applications will recover
- Network output representing *speculative* state must be buffered
  - In the case of failure, the state that produced this output is lost, and not likely to return

Network buffer overview



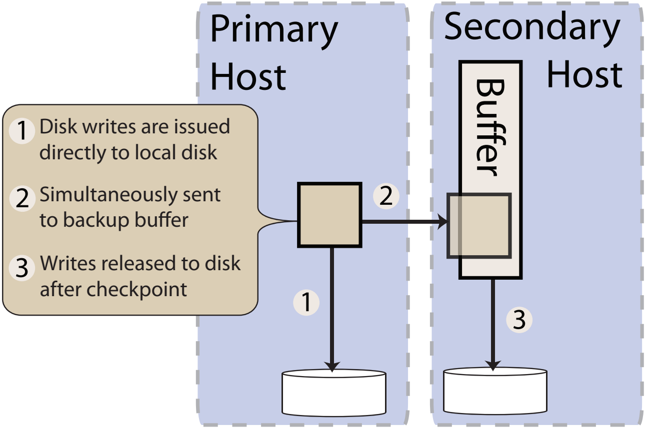
Network buffer implementation

- Implemented as a custom-built queueing discipline
  - Queueing disciplines regulate outbound traffic from network devices. Commonly used to rate-limit (token-bucket) or provide better fairness under congestion (SFQ)
  - Have two basic operations: enqueue and dequeue. In Remus, packets are only dequeued when the state that generated them has been checkpointed
  - Remus sends a message via RTNetlink to the queueing discipline to mark a checkpoint
- Installed over the *IMQ* device
  - *Outbound* traffic from the guest VM is *inbound* traffic for the host
  - Linux queueing disciplines only queue outbound traffic
  - IMQ is a third-party virtual device that accepts inbound traffic and reinjects it specifically to allow inbound queueing

Disk replication principles

- The active disk must be crash-consistent at all times
- In case of failure, disk state at the time of the most recent checkpoint must be available
- At all times, only one physical disk represents the most recent state of the host

Disk replication overview



Disk replication implementation

- Implemented as a *block tap* module
  - The block tap is a Xen device that allows a user-space process to interpose on the block request/response stream between a virtual machine and its devices
- Operates as a client/server pair
- The client
  - Propagates disk write requests to the server at the same time that it passes them to the underlying device
  - Forwards checkpoint messages from Remus to the backup
  - Forwards checkpoint commit messages from the backup to Remus

Disk replication server

- The server maintains two separate buffers
  - The *speculation buffer* receives the write request stream forwarded from the client
  - When a checkpoint message arrives in the stream, it moves the speculation buffer into the *write-out buffer*
- The contents of the write-out buffer are written to disk asynchronously
- In the event of failure, the speculation buffer is discarded
- Execution does not begin on the backup until the write-out buffer has been flushed to disk
  - Once execution has begun, the backup represents externally visible state — its disk image must be at least crash-consistent
  - When the write-out buffer has drained, an activation record is written to disk and execution may resume

Detecting failure

- Failure detection is managed by a simple in-stream heartbeat
  - If the primary times out writing to the backup, or does not receive checkpoint commit acknowledgment, it disables replication
  - If the backup times out reading checkpoint data from the primary, it activate the replicated VM from the most recent completed checkpoint.
- Currently there is no provision for fencing in the case of network partition
  - Bonded NICs on the replication channel may suffice

Test environment

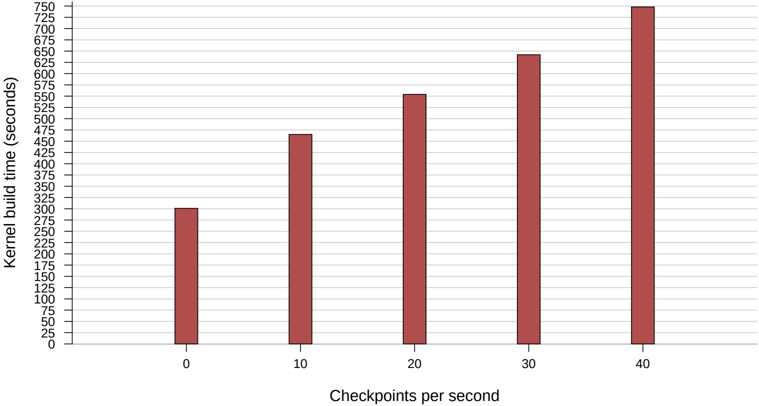
UBC netbed

- Each node is equipped with
  - 1 3.2 GHz Pentium 4 CPU (2 hyperthreads)
  - 3 1Gbps NICs
  - 1024 MB RAM (mostly)
  - 1 80 GB SATA drive
- Nodes are networked
  - One link is for application traffic
  - One link provides administrative access
  - One link is for replication traffic

Failover test

- Test procedure
  - Ping primary every 200ms to measure response time
  - SSH to node, begin kernel compilation
  - Disconnect power to primary node
- Results
  - SSH session remains open
  - Kernel compilation continues to successful completion
  - Ping reports 6 lost packets (1.2 seconds unavailable)

The effect of checkpointing on kernel compilation time



Future work

- Hardware virtualization support
- Introspection optimizations
- Copy-on-write checkpoints
- Deadline scheduler
- Replication stream compression
- Disaster protection

Thank you

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