Dirty Memory Tracking for Performant Checkpointing Solutions

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Software Fault Tolerance

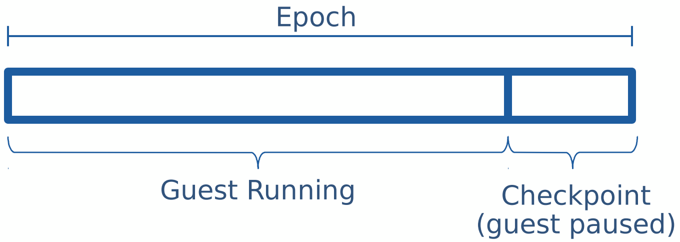
- **Checkpointing is a technique to create a fault tolerant virtual machine by connecting a pair of servers and periodically send VM state from a primary server to a standby server**
  - Checkpointing supplies a greater level of availability relative to typical HA or cluster style solutions in that failures cause no downtime and no data transaction loss.
- **This presentation overviews checkpointing and then describes a set of KVM changes to improve checkpointing performance**

Agenda

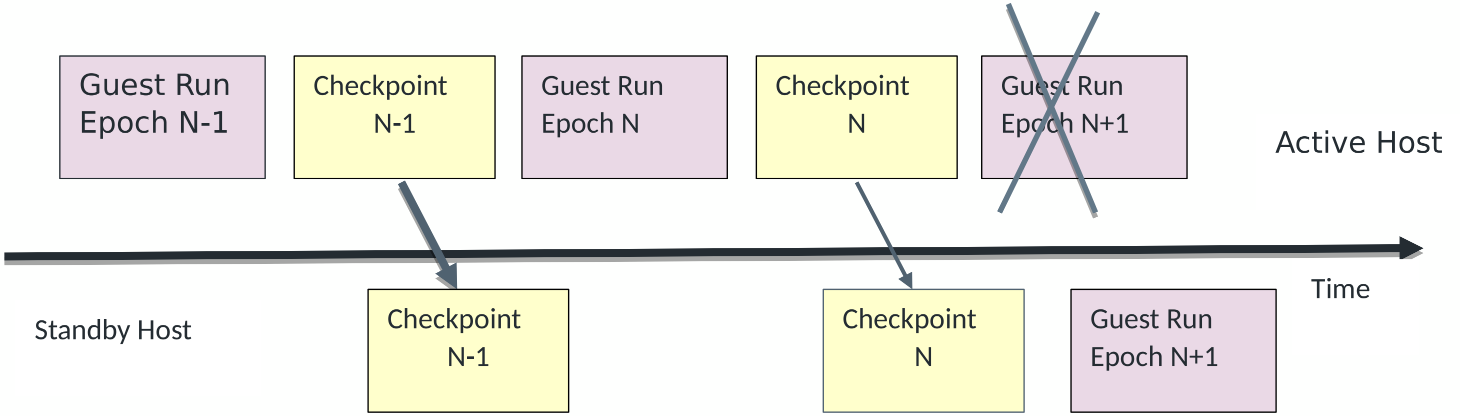
- Fault tolerance via checkpointing
- Motivation
- Design goals
- Proposed KVM Changes
- Upstream status

Checkpointing Overview

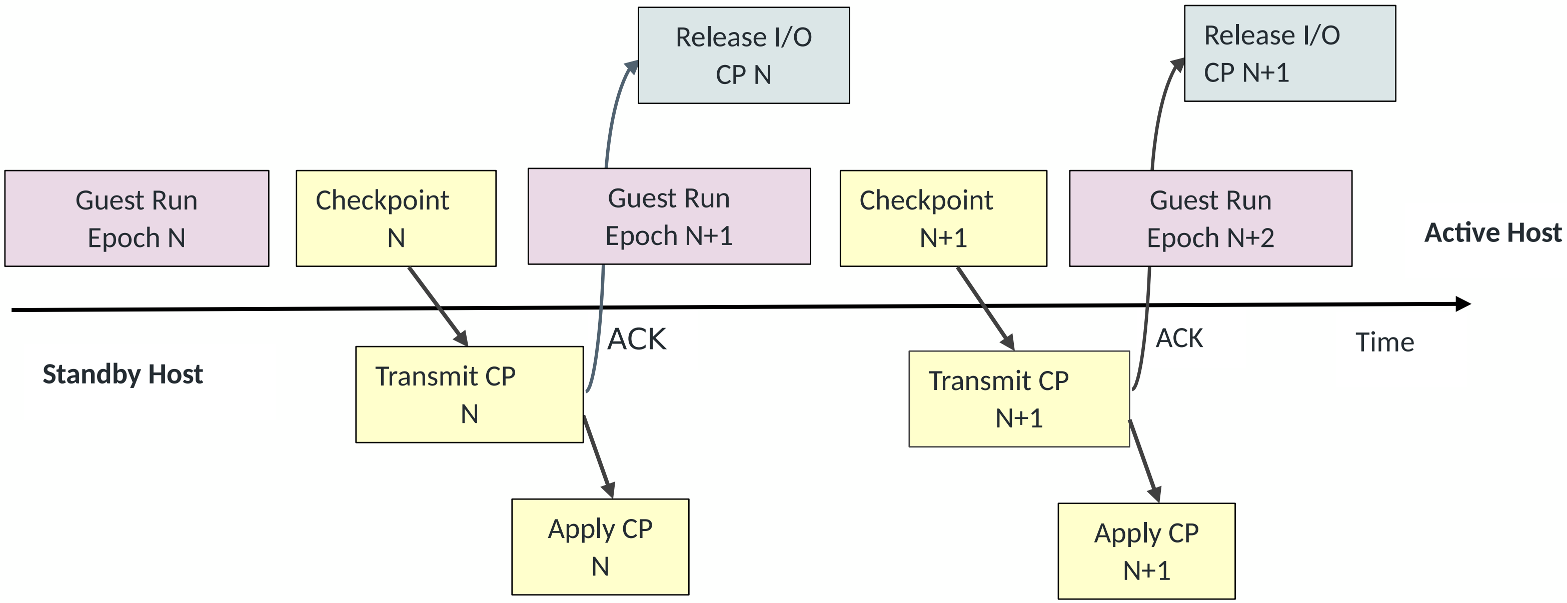
- **A protected guest (OS and applications) runs inside a virtual machine**
- **The hypervisor contains support to:**
  - Pause the VM
  - Capture static and incremental IO state
  - Capture incremental memory state
    - Pages dirtied since last checkpoint
  - Resume the VM



- **The above operations are called a checkpoint**
- **This captured state is sent to another physical (standby) server whose hypervisor runs a paused VM with the same configuration**
- **In case of a failure of the active server/VM, the standby has sufficient state to resume guest operation from the last checkpoint.**



Guest Run Epoch N-1
Checkpoint N-1
Guest Run Epoch N
Checkpoint N
Guest Run Epoch N+1
Active Host
Time
Standby Host
Checkpoint N-1
Checkpoint N
Guest Run Epoch N+1


Release I/O
CP N
Release I/O
CP N+1
Guest Run
Epoch N
Checkpoint
N
Guest Run
Epoch N+1
Checkpoint
N+1
Guest Run
Epoch N+2
Active Host
ACK
ACK
Time
Standby Host
Transmit CP
N
Transmit CP
N+1
Apply CP
N
Apply CP
N+1

Known Open-Source Checkpointing Solutions

Active

- **COLO**
  - A checkpointing enhancement, needs an underlying checkpointing mechanism.
  - Originally released for Xen in 2012 by Intel/Huawei leveraging Remus
  - KVM upstream effort started in 2014 leveraging MicroCheckpointing project
  - Patch submission started 2015, project is very active with widening participation.

Known Open-Source Checkpointing Solutions

Inactive or Less-active

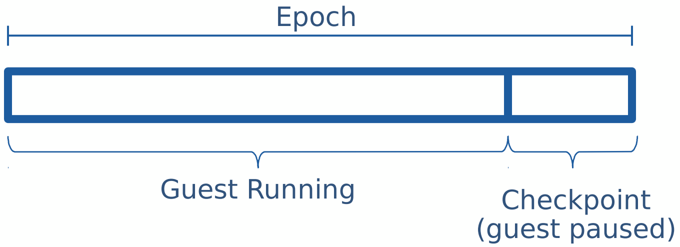
- **Remus**
  - Created in 2007 at the University of British Columbia (and Citrix). Accepted upstream in Xen 4.0 in 2009, no KVM activity.
- **Kemari**
  - Created in 2008 at NTT Cyber Space Labs for Xen. KVM patches created in 2010 but never upstreamed.
- **MicroCheckpointing**
  - Created in 2013 at the IBM Watson Research Center. Upstreaming activity now dormant, possibly superseded by COLO.

Known Proprietary Checkpointing Solutions

- **Vmware FT**
  - 2015 (preceded by a non-checkpointing single core version)
- **Stratus everRun**
  - Build on former Marathon MX product (released in 2010, preceded by non-checkpointing single core version), portions GPL (e.g. KVM mods) and portions proprietary.
- **Avaya Machine Preserving High Availability option for Aura® Application Enablement Services**
  - 2012, available only for Avaya environment (not general purpose)

Motivation for Proposed KVM Changes

- Checkpointing performs anywhere from >90% of a non-checkpointing VM for CPU intensive loads to 25% for high-bandwidth low-latency network intensive loads.
- Realistic commercial workloads typically perform at around 50% of a non-checkpointing VM.
- Majority of a checkpoint is spent on capturing dirty pages



Current Memory Tracking Mechanism

- Use of VM-sized bitmap to track dirty memory
- The number of dirty pages is bounded in a checkpointing system
  - For commercial workloads:
    - Number of checkpoints per second: 150 to 1500
    - Number of dirty pages per checkpoint: 300 to 3000
  - Compare to 2300k total pages (8G VM)
- Traversing a large, sparsely populated bitmap every checkpoint is time-consuming
- Copying bitmap to user space every checkpoint is time-consuming

Design Goals

- **Easily portable to various kernel versions**
  - CentOS 6.4, CentOS 6.5, CentOS 6.6, CentOS 6.7, CentOS 7.2
  - Ubuntu 14.04
  - SLES12
- **No change of existing KVM functionality**
  - New ioctls
- **Co-exist with current dirty memory logging facilities**
- **Usable by live migration as well as checkpointing**
- **Avoid dynamic memory allocation and freeing during checkpointing cycle**
  - Done when VM enters/exists checkpointing mode

Proposed Changes (1 of 3)

Compact lists of dirty GFNs

- One list per online vCPU
  - Avoid locking when vCPUs dirty memory
- One global list
  - Pages dirtied by KVM
  - Overflow dirty pages from per-vCPU lists
- Avoid duplicates via bitmap
  - Duplicates undesirable due to fixed size list
  - Duplicates from guest time update by KVM, PV EOI set/clear by KVM
  - Can reuse current bitmap

Proposed Changes (2 of 3)

Dirty log full force VM exit

- Number of dirty pages is bounded per epoch due to limited buffering
- Exceeding buffer size results in expensive resynchronization
- Force VM exit to user space when number of dirty pages reaches the threshold
- Threshold calculated by user space and passed to KVM during memory tracking initialization

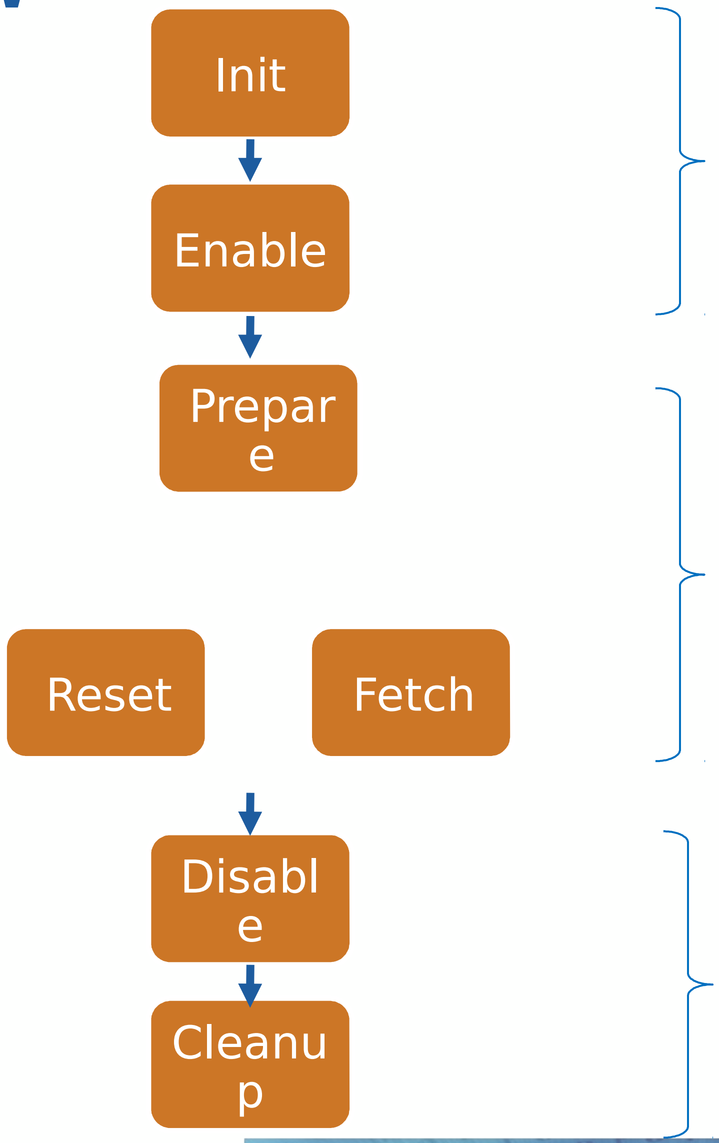
Proposed Changes (3 of 3)

- **Initialization/cleanup (KVM_INIT_MT)**
  - During initialization
    - User space indicates initialization or cleanup
    - User space specifies max number of dirty pages per checkpoint cycle
- **Activate/deactivate (KVM_ENABLE_MT)**
  - Allocate/free dirty lists
  - Enable/disable dirty traps

Proposed Changes (3 of 3) continued

- **Prepare for new checkpoint cycle (KVM_PREPARE_MT_CP)**
  - Reset the indexes/counters for all dirty lists
- **Fetch dirty list (KVM_MT_SUBLIST_FETCH)**
  - Support fetch from multiple user space threads
- **Rearm the dirty traps (KVM_RESET_DIRTY_PAGES)**

Execution flow



Enter checkpointing mode

Checkpoint cycles

Exit checkpointing mode

How about live migration?

- **The proposed changes do not break live migration**
- **Checkpointing mode can be used for live migration**
  - Need user space support
- **Improve the predictability of live migrations of memory write intensive workloads**
  - Autoconverge tries to address this problem via cpu throttling
  - Cpu throttling may not be effective for some workloads where memory write speed is not dependent on CPU execution speed

Upstream Status

- **Version 1 submitted to KVM mailing list**
  - [PATCH 0/6] KVM: Dirty memory tracking for performant checkpointing and improved live migration
  - http://www.spinics.net/lists/kvm/msg131356.html
- **Version 2 planned for September submission**