CloneCloud: Elastic Execution between Mobile Device and Cloud

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31/11/2011
List of contents

1 Introduction
List of contents

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2 Partitioning
List of contents

1. Introduction
2. Partitioning
3. Distributed Execution
List of contents

1. Introduction
2. Partitioning
3. Distributed Execution
4. Implementation and technical details
5. Evaluation
List of contents

1 Introduction
   • Foreword
   • Motivation
   • CloneCloud outline

2 Partitioning
Actual trends

- mobile devices are becoming current computing wave
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- Mobile devices are competing heavily with desktops and laptops for market and popularity.
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- application for mobile devices need more and more resources (computation, storage)
Actual trends

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- mobile devices are competing heavily with desktops and laptops for market and popularity
- they offer even more functionality than laptops (GPS, 3G)
- application for mobile devices need more and more resources (computation, storage)
- mobile devices run on extremely limited supply of energy
The question is:

**Question**

How to solve problem of limited resources of mobile devices and rising demands for computing, storage, etc.?
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**Obvious answer**

Let’s do it in clouds.
The question is:

**Question**

How to do it?
The question is:

**Question**

How to do it?

**Answer**

A lot of different approaches, each of them have some strong and weak points.
The common approach:

Split in traditional client-server paradigm, pushing most computation to the remote server.
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The biggest drawback?

Separate server to each application.
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The biggest drawback?

Separate server to each application.

Examples:
- Online navigations.
- Online dictionaries.
Main goal

"... a flexible architecture for the seamless use of ambient computation to augment mobile device applications, making them fast and energy-efficient."
Goals

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Others aims:
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Others aims:

- allow such grained flexibility on what run where (on mobile or in cloud)
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Main goal
"... a flexible architecture for the seamless use of ambient computation to augment mobile device applications, making them fast and energy-efficient."

Others aims:

- allow such grained flexibility on what run where (on mobile or in cloud)
- take programmer out of the business of application partitioning (make it automatic and seamless)
Clone an unmodified application executable.
Schema

1. Clone an unmodified application executable.
2. The modified executable is running at mobile device.
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7. The remote thread returns back to the mobile device with remotely created state.
Clone an unmodified application executable.
The modified executable is running at mobile device.
At automatically chosen points individual threads migrate from mobile device to a device clone in a cloud.
Remaining functionality on the mobile device keep executing.
Remaining functionality blocks if attempts to access migrated state.
The migrated thread executes on the clone, possibly accessing native features of hosting platforms (fast CPU, hardware accelerators).
The remote thread returns back to the mobile device with remotely created state.
Merge remote and local state back into original process.
Idea

(a) Single-machine computation

(b) Distributed computation
Division

1 Choice where to migrate (made by partitioning component)
Division

1. Choice where to migrate (made by partitioning component)
   - Static Analyzer
Division

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   - Dynamic Profiler
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   - Suspend and Capture
   - Resume and Merge
Overview

Partitioning mechanism decide which parts of an application’s execution retain on the mobile device and which to migrate to the cloud.
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- offline
- any application targeting the application VM platform may be partitioned
- the programmer need no writing any annotation or special idioms
- the partitioning mechanism may be run multiple times for different execution conditions, resulting in a database of partitions
use static analysis to identify legal choices for placing migration and re-integration points in the code. In principle, these points could be place anywhere in the code.
Restriction in CloneCloud

- restrict these points to be method entry (migration points) or method exit (re-integration points).
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- allow migration at VM-layer method boundaries, not native method boundaries
Restriction in CloneCloud

- restrict these points to be method entry (migration points) or method exit (re-integration points).
- allow migration only at boundaries of application method, not core system-library
- allow migration at VM-layer method boundaries, not native method boundaries
- note, however, authors disallow migration while already in native execution, they allow migrated methods to invoke native ones
Property of any legal partition

1. Methods that access specific features of a machine must be pinned to the machine.
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2. Methods that share native state must be collocated at the same machine.
Property of any legal partition

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3. Prevent nested migration.
Dynamic Profiler collects the data that will be used to construct a cost model for the application under different execution settings. The cost metric can vary, but this prototype uses execution time and energy consumed at the mobile device.
the profiler is invoked on multiple executions of the application, each using a randomly chosen set of input data
General mechanism

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- each run executed once on the mobile device and once on the clone in the cloud
General mechanism

- the profiler is invoked on multiple executions of the application, each using a randomly chosen set of input data
- each run executed once on the mobile device and once on the clone in the cloud
- for each execution the output are profile trees $T$ and $T'$, from the mobile device and the clone, respectively
Profile tree

Profile tree is a compact representation of an execution on a single platform.

- one node for each method invocation in the execution
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- method calls in the execution are represented as edges from the node of the caller method invocation (parent) to the nodes of the callees (children)
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- one node for each method invocation in the execution
- rooted at the starting method invocation of the application (e.g. main)
- method calls in the execution are represented as edges from the node of the caller method invocation (parent) to the nodes of the callees (children)
- node is annotated with the cost of its particular invocation in the cost metric (execution time in our case)
every non-leaf node also has a leaf child called its residual node. This node represents the cost of running the body of code excluding the costs of the methods called by it.
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each edge is annotated with the state size at the time of invocation of the child node, plus the state size at the end of that invocation
Profile tree

(a) trace

(b) profile tree
Some math

- collect timings at method entry and exit points
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- compute migration costs (edge weights) by simulating migration at each profiled method
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- compute migration costs (edge weights) by simulating migration at each profiled method
  - perform the suspend-and-capture operation of the migrator
  - measure the captured state size, both when invoking the child node and when returning from it
- fill the profile trees with appropriate values (some converting from size of heaps to time needed to migrate them etc.)
Energy consumption model

We can define also energy consumption model. Authors use a model that maps three system variables to a power level.
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- CPU activity (processing/idle)
- display state (on/off)
- network state (transmitting or receiving/idle)
Optimization Solver

is used to pick which application methods to migrate to the clone from the mobile device, so as to minimize the expected cost of the partitioned application.
General mechanism

What we have?

- particular execution $E$
- two role trees $T$ and $T'$ for execution $E$

What we want to do?
- Optimally replace annotations in $T$ with those in $T'$, so as to minimize the total node and weight cost of the hybrid role tree.

How to do it?
- static analysis dictates the legal ways to fetch annotations from $T'$ into $T$
- dynamic profiling dictates the actual trees $T$ and $T'$
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Translate objective world to math equations

- not all partitioning choices are legal - transform restriction to some relations
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- finally the problem is to minimize the cost

Note
Authors use a standard integer linear programming solver to solve this optimization problem with the above constraints.
Overview

The purpose of the distributed execution mechanism in CloneCloud is to implement a specific partition of an application process running inside an application-layer VM, as determined during partitioning.
General mechanism

The life-cycle of a partitioned application is as follows
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General mechanism

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- When the user attempts to launch a partitioned application, current execution conditions are looked up in a database of pre-computed partitions.
- The application binary loads the partition and instruments the chosen methods with migration and re-integration points-special VM instructions.
The life-cycle of a partitioned application is as follows

- when the user attempts to launch a partitioned application, current execution conditions are looked up in a database of pre-computed partitions
- the application binary loads the partition and instruments the chosen methods with migration and re-integration points-special VM instructions
- when execution of the process on the mobile device reaches a migration point, the executing thread is suspended and its state is packaged and shipped to a synchronized clone
there, the thread state is instantiated into a new thread with the same stack and reachable heap objects, and then resumed
General mechanism

- there, the thread state is instantiated into a new thread with the same stack and reachable heap objects, and then resumed
- when the migrated thread reaches a re-integration point, it is similarly suspended and packaged as before, and then shipped back to the mobile device
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finally, the returned packaged thread is merged into the state of the original process
CloneCloud migration operates at the granularity of a thread.
- allows a multi-threaded process (e.g., a process with a UI thread and a worker thread)
Migrator thread

The thread migrator is a native thread, operating within the same address space as the migrant thread, but outside the virtual machine. As such, the migrator has the ability to view and manipulate both native process state and virtualized state.
General mechanism

- Upon reaching a migration point, the job of the thread migrator is to suspend a migrant thread, collect all of its state, and pass that state to the node manager for data transfer.
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- Remaining threads continue processing, unless they attempt to access such marked (migrated state), in which case they block until the off-loaded thread returns.
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- Remaining threads continue processing, unless they attempt to access such marked (migrated state), in which case they block until the off-loaded thread returns.
- As soon as the captured thread state is transferred to the target clone device, the node manager passes it to the migrator of a freshly allocated process.
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- As soon as the captured thread state is transferred to the target clone device, the node manager passes it to the migrator of a freshly allocated process.
- Reintegration is almost identical conceptually to the original migration (the context must update the original thread state to match the changes effected at the clone instead of creating new one)
State merge

What’s the problem?

What to do with new objects? How to update existing objects? What with deleted objects? Object references themselves are not sufficient in that respect, since in most application-layer VMs, references are implemented as native memory addresses, which look different in different processes, across different devices and possibly architectures, and tend to be reused over time for different objects.
Object mapping table

The solution is object mapping table.
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- use during state capture and reinstatation
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- stored while a thread is executing at a clone
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- CID - unique ID give to object by clone
Object mapping table

How it works:
Object mapping table

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- while migration is initiated - mapping table is created and MID id filled for captured objects
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Object mapping table

How it works:

- while migration is initiated - mapping table is created and MID id filled for captured objects
- clone assign CID for each object
- while reintegration
  - objects with MID null was freshly created (must be allocated at mobile)
  - objects with MID and CID not nulls must be updated
  - object deleted at the clone are ignored and no mapping is send back
List of contents
Introduction
Partitioning
Distributed Execution
Implementation and technical details
Evaluation

General mechanism
Suspend and Capture, Resume and Merge

Object mapping table

<table>
<thead>
<tr>
<th>Reference</th>
<th>MID</th>
<th>CID</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x01</td>
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<td>0x02</td>
<td>2</td>
<td>null</td>
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<tr>
<td>0x03</td>
<td>3</td>
<td>null</td>
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</table>

(1) Mobile Phone

(2) Clone

<table>
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(3) Mobile Phone

<table>
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<th>Reference</th>
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<th>CID</th>
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<tr>
<td>0x05</td>
<td>5</td>
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</table>
Authors implemented prototype of CloneCloud partitioning and migration on the cupcake branch of the Android OS.
Technical details

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- Tested on HTC G1 device equipped with both WiFi and 3G connections
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- Tested on HTC G1 device equipped with both WiFi and 3G connections
- Clones running the Android x86 virtual machine
- Clones execute on a server with a 3.0GHz Xeon CPU, running VMware ESX 4.1
Evaluation

Tested with three implemented
Evaluation

Tested with three implemented

- virus scanner
Evaluation

Tested with three implemented
  - virus scanner
  - image search
Evaluation

Tested with three implemented

- virus scanner
- image search
- privacy-preserving targeted advertising
Evaluation

Static analysis
The static analysis took 23 seconds on average with these application.

Dynamic profiler
Generating an optimizer (ILP) script from the profile trees, constraints and execution conditions, and solving the optimization problem, takes less than one second.
## Execution time

<table>
<thead>
<tr>
<th>Application</th>
<th>Input Size</th>
<th>Phone Exec. (sec) Mean (std)</th>
<th>Clone Exec. (sec) Mean (std)</th>
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</thead>
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<td>6.1 (0.32)</td>
<td>0.2 (0.01)</td>
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<td></td>
<td>1MB</td>
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<td></td>
<td>10MB</td>
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<td>22.5 (0.08)</td>
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<td>IS</td>
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<td>22.1 (0.26)</td>
<td>0.9 (0.07)</td>
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<td></td>
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<td>212.8 (0.44)</td>
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<td>0.2 (0.01)</td>
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<td></td>
<td>depth 4</td>
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<td></td>
<td>depth 5</td>
<td>302.7 (3.76)</td>
<td>10.9 (0.19)</td>
</tr>
</tbody>
</table>
Time save
Energy save

- VS
- IS
- BP

100KB

1 MB

10 MB

Phone
CC-WiFi
CC-3G

Piotr Karasiński
CloneCloud