# Just-in-Time Provisioning for Cyber Foraging

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## ABSTRACT

Cloud offload is an important technique in mobile computing. VM-based cloudlets have been proposed as offload sites for the resource-intensive and latency-sensitive computations typically associated with mobile multimedia applications. Since cloud offload relies on precisely-configured back-end software, it is difficult to support at global scale across cloudlets in multiple domains. To address this problem, we describe just-in-time (JIT) provisioning of cloudlets under the control of an associated mobile device. Using a suite of five representative mobile applications, we demonstrate a prototype system that is capable of provisioning a cloudlet with a non-trivial VM image in 10 seconds. This speed is achieved through dynamic VM synthesis and a series of optimizations to aggressively reduce transfer costs and startup latency.

## Categories and Subject Descriptors

D.4.7 [**Software**]: Operating System – Organization and Design

## General Terms

Experimentation, Measurement, Performance

## Keywords

mobile computing, cloud computing, cloudlet, cloud offload, virtual machine, Amazon EC2, VM synthesis, Wi-Fi, wireless

## 1. INTRODUCTION

*Cloud offload* from mobile devices has been the subject of many recent papers [5, 7, 21, 35]. These efforts are rooted in work stretching back over a decade on the theme of *cyber foraging* [41], whose goal is to overcome the resource limitations of wireless mobile devices. Flinn [8] traces the evolution of this technique and gives a comprehensive review of work in this area. For reasons discussed in Section 2.1, it will remain an important technique for the future despite mobile hardware improvements. *VM-based cloudlets* that are dispersed at the edges of the Internet and located just one WiFi hop away from associated mobile devices have been proposed as cyber foraging sites for cloud offload [42].

Mobile computing today spans many device operating systems and application environments (e.g., Android, iOS, Windows 8), as well as diverse approaches to partitioning and offloading computation. The latter range from language-specific approaches such as MAUI to legacy implementations that depend on specific back-end operating systems and runtime support [1]. There is churn in this space from new OS versions, patches to existing OS versions, new libraries, new versions of cyber foraging tools, new language runtime systems, and so on. VMs cleanly encapsulate this messy complexity, but create the problem of precisely provisioning a cloudlet from a large and continuously evolving space of VM images.

The large size of VM images complicates dynamic provisioning of cloudlets. At the same time, the presumption of *ubiquity* in mobile computing deprecates a static provisioning strategy. A mobile user expects good service for all his applications at any place and time. Wide-area physical mobility (e.g., an international traveler stepping off his flight) makes it difficult to always guarantee that a nearby cloudlet will have the precise VM image needed for cyber foraging (e.g., natural language translation with customized vocabulary and speaker-trained voice recognition via the traveler's smartphone). The VM guest state space is simply too large and too volatile for static provisioning of cloudlets at global scale. A different provisioning challenge involves the deployment of new cloudlets for load balancing, hardware upgrades, or recovery from disasters. Dynamic self-provisioning of cloudlets will greatly simplify such deployments.

*Rapid just-in-time provisioning of cloudlets* is the focus of this paper. We show how a cloudlet can be provisioned in as little as 10 seconds with a complete copy of a new VM image that is the back-end of an offloaded application such as face recognition, object recognition, or augmented reality. The compressed sizes of these VM images can range from 400 MB for a stripped-down Linux guest, to well over 2 GB for typical Windows based images. The key to rapid provisioning is the recognition that a large part of a VM image is devoted to the guest OS, software libraries, and supporting software packages. The customizations of a base system needed for a particular application are usually relatively small. Therefore, if the *base VM* already exists on the cloudlet, only its difference relative to the desired custom VM, called a *VM overlay*, needs to be transferred. This concept of a VM overlay bears resemblance to copy-on-write virtual disk files [25] or VM image hierarchies [3], but extends to both disk and memory snapshots.


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| Year | Typical Server Processor | Speed | Typical Handheld Device | Speed |
|---|---|---|---|---|
| 1997 | Pentium® II | 266 MHz | Palm Pilot | 16 MHz |
| 2002 | Itanium® | 1 GHz | Blackberry 5810 | 133 MHz |
| 2007 | Intel® Core™ 2 | 9.6 GHz (2.4 Ghz x 4 cores) | Apple iPhone | 412 MHz |
| 2011 | Intel® Xeon® X5 | 32 GHz (2.7 GHz x 6 cores x 2 sockets) | Samsung Galaxy S2 | 2.4 GHz (1.2 GHz x 2 cores) |

**Table 1: Hardware Performance (adapted from Flinn [8])**

Our approach of using VM overlays to provision cloudlets is called *dynamic VM synthesis*. Proof-of-concept experiments [42] showed provisioning times of 1–2 minutes using this approach. In this paper, we present a series of optimizations that reduces this time by an order of magnitude.

Although motivated by mobile computing, dynamic VM synthesis has broader relevance. Today, public clouds such as Amazon's EC2 service are well-optimized for launching images that already exist in their storage tier, but do not provide fast options for provisioning that tier with a new, custom image. One must either launch an existing image and laboriously modify it, or suffer the long, tedious upload of the custom image. For really large images, Amazon recommends mailing a hard drive! We show that dynamic VM synthesis can rapidly provision public clouds such as EC2.

# 2. BACKGROUND

## 2.1 Need for Cyber Foraging

The initial observation that mobile devices are resource-poor relative to server hardware of comparable vintage dates back to the mid-1990s [40]. Table 1, adapted from Flinn [8], illustrates the consistent large gap in the processing power of typical server and mobile device hardware between 1997 and 2011. This stubborn gap reflects a fundamental reality of user preferences: Moore's Law has to be leveraged differently on hardware that people carry or wear for extended periods of time. This is not just a temporary limitation of current mobile hardware technology, but is intrinsic to mobility. The most sought-after features of a mobile device always include light weight, small size, long battery life, comfortable ergonomics, and tolerable heat dissipation. Processor speed, memory size, and disk capacity are secondary. For as long as our appetite for resource-intensive applications exceeds what mobile devices can sustain, cyber foraging will continue to be relevant.

Today, tasks such as free-form speech recognition, natural language translation, face recognition, object recognition, dynamic action interpretation from video, and body language interpretation lie beyond the limits of standalone mobile computing technology. Table 2, from Ha et al. [16], shows the median and 99th percentile response times for speech recognition and face recognition on typical mobile hardware in 2012, with and without offloading. The results show that cloud offload improves both the absolute response times and their variance. Looking further into the future, one can imagine cognitive assistance applications built from these primitives (such as an advanced version of IBM's Watson [51]) seamlessly augmenting human perception and cognition, and assisting attention-challenged mobile users in their real-world and cyber-world interactions. Cyber foraging will be essential to realizing such a futuristic world.

| Application | No Offload median | No Offload 99% | Offload median | Offload 99% |
|---|---|---|---|---|
| SPEECH | 1.22 s | 6.69 s | 0.23 s | 1.25 s |
| FACE | 0.42 s | 4.12 s | 0.16 s | 1.47 s |

**Table 2: Speech and Face Recognition Today (Source: [16])**

## 2.2 VM-based Cloudlets

Which specific part of the infrastructure should one leverage for cyber foraging? The obvious answer today is "the cloud." Public cloud infrastructure such as Amazon EC2 data centers are natural offload sites for resource-intensive computations triggered by mobile devices. Unfortunately, these large consolidated data centers are suboptimal offload sites for a growing number of resource-intensive yet latency-sensitive mobile applications. In the course of its travels, a roaming mobile device often sees multiple network hops to such a data center [49]. The resulting end-to-end latency can be large enough to seriously affect many emerging mobile applications [16]. In hostile environments such as military operations and disaster recovery, physical distance also increases vulnerability to network disruptions [44].

A cloudlet is a new architectural element for cyber foraging that represents the middle tier of a 3-tier hierarchy: mobile device – cloudlet – cloud. To serve as shared infrastructure, a cloudlet must provide safety and strong isolation between untrusted computations from different mobile devices. To sustain viable business models, it has to incorporate authentication, access control, and metering mechanisms, and has to meet service level expectations/guarantees through dynamic resource management. To be cost-effective, cloudlet deployments need to support the widest possible range of user-level computations, with minimal restrictions on their process structure, programming languages or operating systems.

In public and private clouds, these requirements are met using the VM abstraction. For precisely the same reasons, VMs are also valuable as the organizing principle of cloudlets. An important difference is that cloudlets only contain soft state that is cached or otherwise re-creatable, while clouds contain both hard and soft state. In the context of this paper, the most important components of "state" are VM images. A cloudlet can thus be viewed as a "data center in a box" that "brings the cloud closer." Today, "micro data centers" from companies such as Myoonet [28] and AOL [26] are already available and can be repurposed as cloudlets.

# 3. DYNAMIC VM SYNTHESIS

## 3.1 Basic Approach

The intuition behind dynamic VM synthesis is that although each VM customization is unique, it is typically derived from a small set of common base systems such as a freshly-installed Windows 7 guest or Linux guest. We refer to the VM image used for offloading as a *launch VM*. It is created by installing relevant software into a *base VM*. The compressed binary difference between the base VM image and the launch VM image is called a *VM overlay.* This idea of a binary difference between VM images to reduce storage and network transfer costs has been successfully used before [3, 25, 57]. We, therefore, extensively use this overlay concept for both VM disk and memory snapshots in this work.

At run-time, *dynamic VM synthesis* (sometimes shortened to "VM synthesis" or just "synthesis") reverses the process of overlay creation. Figure 1 shows the relevant steps. A mobile device delivers the VM overlay to a cloudlet that already possesses the base VM from which this overlay was derived. The cloudlet decompresses the overlay, applies it to the base to derive the launch VM, and then

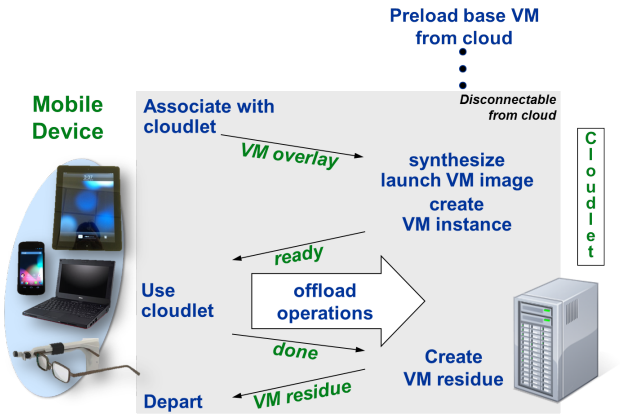


**Figure 1: Dynamic VM Synthesis from Mobile Device**

creates a VM instance from it. The mobile device can now begin performing offload operations on this instance. The instance is destroyed at the end of the session, but the launch VM image can be retained in a persistent cache for future sessions. As a slight variant of this process, a mobile device can ask the cloudlet to obtain the overlay from the cloud. This indirection reduces the energy used for wireless data transmission, but can improve transfer time only when WAN bandwidth to the cloud exceeds local WiFi bandwidth.

Note that the cloudlet and mobile device can have different hardware architectures: the mobile device is merely serving as transport for the VM overlay. Normally, each offload session starts with a pristine instance of the launch VM. However, there are some use cases where modified state in the launch VM needs to be preserved for future offloads. For example, the launch VM may incorporate a machine learning model that adapts to a specific user over time. Each offload session then generates training data for an improved model that needs to be incorporated into the VM overlay for future offload sessions. This is achieved in Figure 1 by generating a *VM residue* that can be sent back to the mobile device and incorporated into its overlay.

There are no constraints on the guest OS of the base VM; our prototype works with both Linux and Windows. We anticipate that a relatively small number of base VMs will be popular on cloudlets at any given time. To increase the chances of successful synthesis, a mobile device can carry overlays for multiple base VMs and discover the best one to use through negotiation with the cloudlet. Keep in mind that the VMs here are virtual appliances that are specifically configured for serving as the back-ends of mobile applications. Although these virtual appliances are generated on top of conventional operating systems such as Linux or Windows, they are focused and dedicated to serve a particular mobile application, rather than general-purpose desktop environments that need a wider range of functionality.

It is useful to contrast dynamic VM synthesis with demand paging the launch VM from the mobile device or cloud using a mechanism such as the Internet Suspend/Resume system® [43]. Synthesis requires the base VM to be available on the cloudlet. In contrast, demand paging works even for a freshly-created VM image that has no ancestral state on the cloudlet. Synthesis can use efficient streaming to transmit the overlay, while demand paging incurs the overhead of many small data transfers. However, some of the state that is proactively transferred in an overlay may be wasted if the launch VM includes substantial state that is not accessed. Synthesis incurs a longer startup delay before VM launch. However, once launched, the VM incurs no stalls. This may be valuable for soft real-time mobile applications such as augmented reality.

**OBJECT:** identifies known objects and their positions in an image. Originally intended for a robotics application [48], it computes SIFT features [24] to match objects from a database, and computes position based on geometry of matched features. The back-end of this application runs in a Linux environment.

**FACE:** detects and attempts to identify faces in an image from a prepopulated database. The algorithm uses Haar Cascades of classifiers for detection and the Eigenfaces method [52] for identification. The application backend is based on OpenCV [32] computer vision routines, and runs on Microsoft Windows 7.

**SPEECH:** performs speech-to-text conversion of spoken English sentences using a Hidden Markov Model (HMM) recognition system [47]. The Java-based application backend runs on Linux.

**AR:** [50] is an augmented reality application that identifies buildings and landmarks in a scene captured by a phone's camera, and labels them precisely in the live view. An 80 GB database constructed from over 1000 images of 200 buildings is used to perform identification. The application backend uses multiple threads, OpenCV [32] libraries, and runs on Microsoft Windows 7.

**FLUID:** is an interactive fluid dynamics simulation, that renders a liquid sloshing in a container on the screen of a phone based on accelerometer inputs. The application backend runs on Linux and performs a smoothed particle hydrodynamics [46] physics simulation using 2218 particles, generating up to 50 frames per second. The structure of this application is representative of real-time (i.e., not turn-based) games.

**Figure 2: Example Mobile Multimedia Applications**

It is also useful to contrast VM synthesis with launching the base VM and then performing package installations and configuration modifications to transform it into the launch VM. This is, of course, exactly what happens offline when creating the overlay; the difference is that the steps are now being performed at runtime on each association with a cloudlet. On the one hand, this approach can be attractive because the total size of install packages is often smaller than the corresponding VM overlay (e.g., Table 3) and, therefore, involves less transmission overhead. On the other hand, the time delay of installing the packages and performing configuration is incurred at run time. Unlike optimization of VM synthesis, which is fully under our control even if the guest is closed-source, speeding up the package installation and configuration process requires individual optimizations to many external software components. Some of those may be closed-source, proprietary components. Of even greater significance is the concern that installing a sequence of packages and then performing post-installation configuration is a fragile and error-prone task even when scripted. Defensive engineering suggests that these fragile steps be performed only once, during offline overlay creation. Once a launch VM image is correctly created offline, the synthesis process ensures that precisely the same image is re-created on each cloudlet use. This bit-exact precision of cloudlet provisioning is valuable to a mobile user, giving him high confidence that his applications will work as expected no matter where he is in the world. Finally, the installation approach requires the application to be started fresh every time. Execution state is lost between subsequent uses, destroying any sense of seamless continuity of the user experience.

## 3.2 Baseline Performance

We have built an instantiation of the basic VM synthesis approach, using the KVM virtual machine monitor. In our prototype, the overlay is created using the `xdelta3` binary differencing tool. Our experience has been that `xdelta3` generates smaller overlays than the native VM differencing mechanism provided by KVM. The VM overlay is then compressed using the Lempel-Ziv-Markov algorithm (LZMA), which is optimized for high compression ra-

| App name | Install size (MB) | Overlay Size (MB) disk | memory | Synthesis time (s) |
|---|---|---|---|---|
| OBJECT | 39.5 | 92.8 | 113.3 | 62.8 |
| FACE | 8.3 | 21.8 | 99.2 | 37.0 |
| SPEECH | 64.8 | 106.2 | 111.5 | 63.0 |
| AR | 97.5 | 192.3 | 287.9 | 140.2 |
| FLUID | 0.5 | 1.8 | 14.1 | 7.3 |

**Table 3: Baseline performance (8 GB disk, 1 GB memory)**

tios and fast decompression at the price of relatively slow compression [54]. This is an appropriate trade-off because decompression takes place in the critical path of execution at run-time and contributes to user-perceived delay. Further, compression is only done once offline but decompression occurs on each VM synthesis.

We test the efficacy of VM synthesis in reducing data transfer costs and application launch times on the VM back-ends of five mobile applications, summarized in Figure 2. In each case, user interaction occurs on a mobile device while the compute-intensive back-end processing of each interaction occurs in a VM instance on a cloudlet. These applications, written by various researchers and described in recent literature, are the building blocks of futuristic applications that seamlessly augment human perception and cognition. Three of the five back-ends run on Linux, while the other two run on Windows 7. These compute-intensive yet latency-sensitive applications are used in all the experiments reported in this paper.

We first construct base VM images using standard builds of Linux (Ubuntu 12.04 server) and Windows 7. These VMs are configured with 8 GB of disk and 1 GB of memory. An instance of each image is booted and then paused; the resulting VM disk image and memory snapshot serve as *base disk* and *base memory* respectively. To construct a launch VM, we resume an instance of the appropriate base image, install and configure the application binaries, and launch the application. At that point, we pause the VM. The resulting disk image and memory snapshot constitute the launch VM image. As soon as an instance is resumed from this image, the application will be in a state ready to respond to offload requests from the mobile device — there will be no reboot delay.

The overlay for each application is the compressed binary difference between the launch VM image and its base VM image, produced using `xdelta3` and LZMA compression. The sizes of the overlays, divided into disk and memory components, are reported in Table 3. For comparison, the sizes of the compressed application installation packages are also reported. Relative to VM image sizes, the VM synthesis approach greatly reduces the amount of data that must be transferred to create VM instances. Compared to the launch VM images (nominal 8 GB disk image plus memory snapshot), Table 3 shows that overlays are an order of magnitude smaller. While they are larger than the install packages from which they were derived, VM synthesis eliminates the fragile and error-prone process of runtime package installation and configuration as discussed in Section 3.1. In fact, as we show later in Section 8.1, provisioning using the most optimized version of VM synthesis is faster than runtime installation and configuration.

The total time to perform VM synthesis is also reported in Table 3. These times were measured using a netbook (client) and a virtual machine (server) hosted in a cloudlet described in Table 4. The client serves the application overlays to the cloudlet, which performs synthesis and executes the application VMs. For each application, the total time reported includes the time needed to transfer the overlay across WiFi, decompress it, apply the overlay to the base image, and resume the constructed application image. We note that the netbook used here is not significantly more capable

| | Mobile | Cloudlet |
|---|---|---|
| Model | Dell™ Latitude 2120 Netbook | Dell™ Optiplex 9010 Desktop |
| CPU | Intel® Atom™ N550 1.5 GHz, 2 cores | Intel® Core® i7-3770 3.4 GHz, 4 cores, 8 threads (4 VCPUs for VM) |
| RAM | 2 GB | 32 GB (1 GB VM RAM) |
| Disk | 250 GB HDD | 1 TB HDD (8 GB VM disk) |
| Network | 802.11a/g/n WiFi* | 1 Gbps Ethernet |
| OS | Ubuntu 12.04 64bit (Linux kernel 3.2.0) | Ubuntu 12.04 64bit (Linux kernel 3.2.0) |
| VMM | — | QEMU/KVM-1.1.1† |
| misc | Belkin N750 Router (802.11n, GigE) | |

*2.4 GHz 802.11n used here; 38 Mbps measured average BW
†modified for some experiments, as described in Sect. 7.2

**Table 4: System configuration for experiments**

than smartphones today, and achieves the same network bandwidth (38 Mbps) on 802.11n as the Samsung Galaxy 2 in our tests. Since most computation is done offline or on the cloudlet, and the data transfer is network limited, we do not expect significantly different results using a smartphone. However, for our prototype implementation, the netbook was convenient as it allowed us to use a full complement of x86 tools and libraries for the front-ends of our five applications. We use this configuration for all of the experiments in this paper.

Although this baseline implementation of VM synthesis achieves bit-exact provisioning without transferring full VM images, its performance falls short for ad-hoc, on-demand use in mobile offload scenarios. Table 3 shows that only one of the applications, FLUID, completes synthesis within 10 seconds. A synthesis time of 60 to 150 seconds is more typical for the other applications. That is too large for good user experience.

In the rest of this paper, we present a multi-pronged approach to accelerating VM synthesis. We first reduce the size of the overlay using aggressive deduplication (Section 4) and by bridging the semantic gap between the VMM and guest OS (Section 5). We then accelerate the launch of the VM image by pipelining its synthesis (Section 6), and by optimistically launching before synthesis is complete (Section 7). The results presented in each of these sections shows the speedup attributable to that optimization.

# 4. DEDUPLICATION

## 4.1 Concept

Our first optimization leverages the fact that there are many sources of data redundancy in a VM overlay. Through deduplication we can eliminate this redundancy and thus shrink the overlay. A smaller overlay incurs less transmission delay and also consumes less energy on the mobile device for transmission. Deduplication is very effective at reducing redundant data, and has been used widely in a variety of fields. In the virtualization space, it has been applied to reduce memory footprints of concurrent VMs [53], and in accelerating VM migration [57]. It is particularly well suited to VM overlays, since the significant expense of deduplication is only incurred offline during overlay construction. The overhead of re-inflating deduplicated data during synthesis is trivial, especially because the cloudlet is a powerful machine that is not energy-constrained. From a number of sources, we can anticipate some duplication of data between the memory snapshot and the disk image of the launch VM. For example, at the moment the launch VM is suspended during overlay construction, the I/O buffer cache of the guest OS contains some data that is also present in its virtual disk. Additionally, data from some files on the virtual disk may

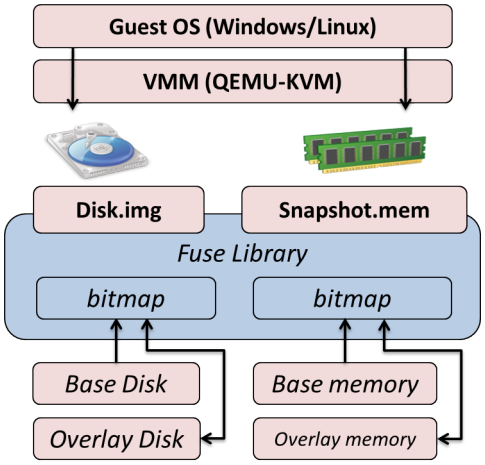


**Figure 3: FUSE Interpositioning for Deduplication**

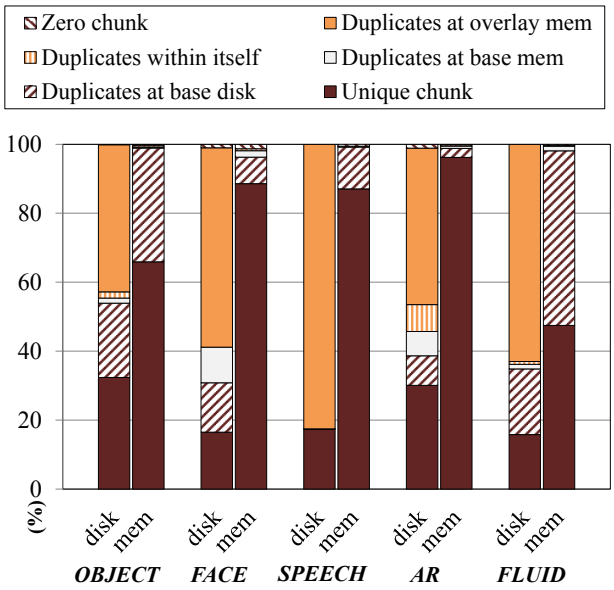


**Figure 4: Benefit of Deduplication**

have been read by the application back-end into its virtual memory during initialization. Further, depending on the runtime specifics of the programming language in which the application is written, there may be copies of variable initialization data both in memory and on disk. These are only a few of the many sources of data duplication between the memory snapshot and the disk image of the launch VM.

Separately, we can also expect some duplication of data between the overlay and the base VM (which is already on the cloudlet). Recall that the baseline implementation in Section 3.1 creates a VM overlay by constructing a binary delta between a launch VM and the base VM from which it is derived. This binary delta may contain duplicate data that has been copied or relocated within the memory or disk image. Indeed, the baseline system cannot take advantage of the fact that many parts of memory should be identical to disk because they are loaded from disk originally, e.g., executables, shared libraries, etc. An efficient approach to capturing this begins with a list of modifications within the launch VM and then performs deduplication to further reduce this list to the minimal set of information needed to transform a base VM into the launch VM. If we could find this minimal set, then we could construct smaller VM overlays.

## 4.2 Implementation

The choice of the granularity at which comparisons are performed is a key design decision for deduplication. Too large a granularity will tend to miss many small regions that are identical. Very small granularity will detect these small regions, but incur large overhead in the data representation. Our choice is a chunk size of 4 KB because it is a widely-used page size for many popular operating systems today. For example, current versions of Linux, Mac OS X, and Windows all use a 4 KB page size. An additional benefit of deduplicating at this granularity is that most operating systems use Direct Memory Access (DMA) for I/O, which means the disk is accessed with memory page size granularity. Thus, the 4 KB chunk size is likely to work well for both memory and disk deduplication.

To discover the portions of disk and memory modified during the process of creating a launch VM, we introduce a shim layer between the VMM and the backing files for virtual disk and memory using FUSE, as shown in Figure 3. During the installation and configuration steps of launch VM construction, the shim layer exposes I/O requests from the VMM to the virtual disk file and memory snapshot file. On every write to either the virtual disk or memory snapshot, we redirect the write to the corresponding overlay file and mark a bitmap indicating this chunk has changed. When reads occur at a later point in time, we consult this bitmap to determine if the read should be serviced from the original base files, or from the new overlay files. As in [30], we have found that FUSE has minimal impacts on virtual disk accesses, despite the fact that it is on the critical read and write paths from the VM to its disk. However, memory operations would become prohibitively expensive with this additional component. We therefore do not use FUSE to capture memory changes. Rather, we capture the entire memory snapshot only after we finish customizing the launch VM. We then interpret this memory snapshot, and compare it with *base memory* to obtain the modified memory chunks and corresponding bitmap.

We reuse this FUSE shim layer at VM synthesis time to avoid the data copying that would be required to explicitly merge the overlay virtual disk/memory with the base to reconstruct the launch VM. Instead, we redirect VM disk/memory access to either the overlay or the base image based on the bitmap. This approach to just-in-time reconstruction of a launch image has been used previously in systems such as ISR [20] and the Collective [3], though only for VM disk.

Once we have a list of modified disk and memory chunks, we perform deduplication by computing SHA-256 hashes [12] of their contents. We use these hashes to construct a unique set of pages which are not contained within the base VM and must be included in the transmitted overlay. We construct the set of unique modified disk and memory chunks using five comparison rules: (1) compare to base VM disk chunks, (2) compare to base VM memory chunks, (3) compare to other chunks within itself (within modified disk or modified memory respectively), (4) compare to a zero-filled chunk, and (5) compare between modified memory and modified disk. These five comparison rules capture various scenarios that are frequent sources of data redundancy, as discussed in Section 4.1.

For each unique chunk, we compare it to the corresponding chunk (same position on disk or in memory) in the base VM. We use the `xdelta3` algorithm to compute a binary delta of the chunk and transmit only the delta if it is smaller in size than the chunk. The idea behind this is that even if the hashes do not match, there may still be significant overlap at a finer byte granularity which a binary delta algorithm can leverage.

## 4.3 Evaluation

Figure 4 shows the benefit of deduplication for the overlay of each application. For any deduplication between memory and disk, we choose to only retain the duplicated chunks within memory. For deduplication purposes, it does not matter if the canonical chunk resides within disk or memory; we chose the memory snapshot as the canonical source of chunks.

Averaged across the five applications, only 22% of the modified disk and 77% of the modified memory is unique. The biggest source of redundancy is between modified memory and modified disk: each application exhibits greater than 58% duplication, with SPEECH exhibiting 83% duplication. The base disk is the second biggest source of duplication. On average, 13% of the modified disk and 21% of the modified memory are identical with chunks in the base disk. We analyzed files associated with the duplicated chunks for the OBJECT application. Our findings are consistent with our intuition: most of the associated files in the modified disk are shared resources located within the `/usr/shared/`, `/usr/lib/`, and `/var/lib/` directories, and a large portion of the files are shared libraries such as `libgdk-x11`, `libX11-xcb`, and `libjpeg`. The overlay memory shows similar results, but it also includes copies of executed binaries such as `wget`, `sudo`, `xz`, `dpkg-trigger`, and `dpkg-deb` in addition to shared libraries.

# 5. BRIDGING THE SEMANTIC GAP

## 5.1 Concept

The strong boundary enforced by VM technology between the guest and host environments is a double-edged sword. On the one hand, this strong boundary ensures isolation between the host, the guest, and other guests. On the other hand, it forces the host to view each guest as a black box, whose disk and memory contents cannot be interpreted in terms of higher-level abstractions such as files or application-level data structures. This challenge was first recognized by Chen and Noble [4]. Various attempts to bridge the semantic gap between VMM and the guest include VM introspection for intrusion and malware detection [13, 18] and memory classification [2] for improving prefetcher performance.

The semantic gap between low-level representations of memory and disk, and higher-level abstractions is also problematic when constructing VM overlays. For example, suppose a guest application downloads a 100 MB file, and later deletes it. Ideally, this should result in no increase in the size of the VM overlay. However, the VMM will see up to 200 MB of modifications: 100 MB of changed disk state, and 100 MB of changed memory state. This is because the file data moves through the in-memory I/O buffer cache of the guest OS before reaching the disk, effectively modifying both memory state and disk state. When the file is deleted, the guest OS marks the disk blocks and corresponding page cache entries as free, but their (now garbage) contents remain. To the VMM, this is indistinguishable from important state modifications that need to be preserved. Deduplication (described in Section 4) can cut this state in half, but we would still unnecessarily add 100 MB to the overlay.

Ideally, only the state that actually matters to the guest should be included in the overlay. When files are deleted or memory pages freed, none of their contents should be incorporated into the overlay. In essence, we need semantic knowledge from the guest regarding what state needs to be preserved and what can be discarded. When constructing the launch VM, a user (or application developer) installs a back-end application server on the base VM. This installation process typically involves several steps including downloading installation packages, creating temporary files, and moving executable binaries to target directories. Also, it is likely that all unneeded files will be deleted after finishing the installation process. We note that there is nothing unusual about this procedure for constructing custom VMs; it is identical to how custom VMs are typically generated in Amazon EC2, for example. We wish to fully leverage the user's intent when producing the overlay. We discard chunks containing semantically unnecessary footprint of the installation process by bridging the semantic gap between the VMM and guest in a manner that is transparent to guests.

In separate sections below, we show how this semantic gap can bridged for disk and memory state.

## 5.2 Implementation: Disk

To accurately account for disk blocks that are garbage, we need either (1) a method of communicating this information from the guest OS to the host, or (2) a method of scanning the contents of the file system on the virtual disk to glean this OS-level information. The first approach requires guest support, and may not be possible for every guest OS. The second approach requires no guest support, but does require an understanding of the on-disk file system format. Both approaches may be used in tandem to cross-check their results.

**Exploiting TRIM support:** The TRIM command in the ATA standard enables an OS to inform a disk which sectors are no longer in use. This command is important for modern devices such as Solid State Drives (SSDs) which implement logic to aggressively remap writes to unused sectors. Wear-leveling algorithms and garbage collection inside of SSDs use this knowledge to increase write performance and device life.

The TRIM command provides precisely the mechanism we desire — an industry-standard mechanism for communicating semantic information about unused sectors from an OS to the underlying hardware. We can exploit this mechanism to communicate free disk block information from the guest OS to the host to reduce VM overlay size. We modify the VMM (KVM/QEMU) to capture TRIM events and to log these over a named pipe to our overlay generation code. When generating the overlay, we merge this TRIM log with a trace of sector writes by timestamp to determine which blocks are free when the VM is suspended; these blocks can be safely omitted from the overlay. To make use of this technique, we simply need to ensure that TRIM support is enabled in the guest OS. As TRIM is an industry standard, it is supported by almost all modern operating systems, including recent Linux distributions and Windows 7.

**Introspecting the file system:** An alternative approach is to use knowledge of the on-disk file system format to directly inspect the contents of a virtual disk [19, 37] and determine which blocks are currently unused. Many file systems maintain lists of free blocks forming a canonical set of blocks which should not be included in an overlay. In the worst case, the entire file system can be crawled to determine which blocks are in use by files within the file system. Although this approach is file-system-specific, it avoids the need to communicate information from a running guest, or to carefully trace TRIM and write events.

We identify free disk blocks using the tool described by Richter et al. [37]. This tool reads and interprets a virtual disk image and produces a list of free blocks. It supports the `ext2/3/4` family of Linux file systems and the `NTFS` file system for Windows.

## 5.3 Implementation: Memory

It is difficult to determine which memory pages are considered free by a guest OS. Although the VMM can inspect the page tables, this is not sufficient to determine if a page is in use because

unmapped pages are not necessarily free [2]. Inspecting page contents is also not good enough, because free pages normally contain random data and are not zeroed.

To bridge this gap, there are two natural approaches: (1) communicate free page information from the guest OS to the host, or (2) interpret memory layout data structures maintained by the guest OS. Unfortunately, there is no standard way of accomplishing the first approach (i.e., no memory counterpart to TRIM support), so we focus our efforts on the second approach. In order to obtain the list of free memory pages we first introduce a tiny kernel module into Linux guests. This module exposes the memory addresses of two data structures for memory management through the `/proc` file system in the guest. We suspend the VM, and feed these addresses and the memory snapshot to an offline scanning program. This scanning program reads the memory snapshot and parses the memory management data structures at the specified addresses to identify the free pages.

Since our approach requires modifying the guest OS, it is not usable on closed-source OSs such as Windows. Further, in-memory data formats tend to be highly volatile across OS releases, and to evolve much more rapidly than file system formats. Even an open-source kernel such as Linux will require significant maintenance effort to track these changes.

Other techniques could be employed to infer free pages without the need for guest support. For example, a VMM could monitor memory accesses since the guest's boot and keep track of pages that have been touched. This would avoid guest modification at the cost of lower fidelity—some of the pages reported as used could have been touched, but later freed. Perhaps with the advent of Non-Volatile Memories (NVMs), which provide persistent storage with memory-like, byte-addressable interfaces, there may be a need to introduce a standardized TRIM-like feature for memory. Such support would make it possible to bridge the memory semantic gap in an OS-agnostic way in the future.

## 5.4 Evaluation

For the disk semantic gap, our experiments show that the TRIM and introspection approaches produce nearly identical results. Just a few additional free blocks are found by the introspection approach that were not captured by TRIM. We therefore present only the results for the TRIM approach.

Figure 5 shows how much we gain by closing the disk semantic gap. For each application we construct the VM image by downloading its installation package, installing it, and then deleting the installation package. We therefore expect our approach to find and discard the blocks that held the installation package, reducing overlay size by approximately the installation package size. Our results confirm this for all of the applications except one: for FACE, the semantically discarded disk blocks together were smaller than the installation package. On investigation, we found that this was due to the freed blocks being reused post-install. On average, across the five applications, bridging the disk semantic gap allows 25% of modified disk chunks to be omitted from the overlay.

Figure 5 also shows the savings we can achieve by discarding free memory pages from the VM overlay. We can discard on average 18% of modified memory chunks for the Linux applications OBJECT, SPEECH, and FLUID. Since our implementation is limited to Linux, we cannot reduce the memory overlays for the two Windows-based applications (FACE and AR).

Combining deduplication and bridging of the semantic gap can be highly effective in reducing the VM overlay size. Figure 6 shows VM overlay size with each optimization individually represented, and also combined together. The "baseline" represents VM overlay size using the approach described in Section 3. The bar labeled "deduped" is the VM overlay with deduplication applied; "semantics" is the VM overlay with semantic knowledge applied (only disk for Windows applications); and, "combined" is the VM overlay size with both optimizations applied. On average compared to the baseline implementation, the deduplication optimization reduces the VM overlay size to 44%. Using semantic knowledge reduces the VM overlay size to 55% of its baseline size. Both optimizations applied together reduce overlay size to 28% of baseline.

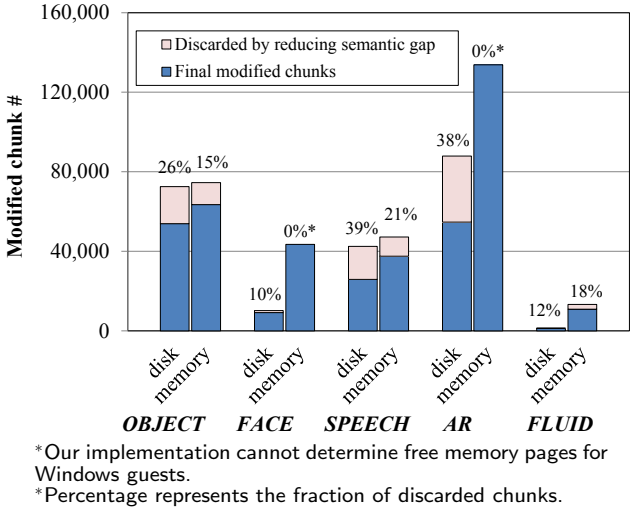


**Figure 5: Savings by Closing the Semantic Gap**

The final overlay disk almost disappears when we combine both optimizations. This is because a large portion of disk chunks are associated with installation packages. Recall that to install each application, we first download an installation package in the VM and remove it later when it finishes installation. This installation file is already compressed, so further compression does little. In addition, this newly introduced data is less likely to be duplicated inside the base VM. Therefore, applying semantic knowledge removes most of the unique chunks not found by deduplication. For example in AR, 25,887 unique chunks remained after deduplication, but 96% of them are discarded by applying semantic knowledge.

# 6. PIPELINING

## 6.1 Concept

There are three time-consuming steps in VM synthesis. First, the VM overlay is transferred. Next, the VM overlay is decompressed. Finally, the decompressed VM overlay is applied to the base VM (i.e., `xdelta3` in reverse). These steps are serialized because we need the output of the preceding step as input to the next one, as shown in Figure 7. This serialization adds significantly to the VM start latency on a cloudlet. If we could begin the later steps before the preceding ones complete, we could shrink the total time for synthesis as shown in Figure 8.

## 6.2 Implementation

The implementation follows directly from the pipelining concept. We split the VM overlay into a set of segments and operate on each segment independently. The VM synthesis steps can now be pipelined. The decompression of a segment starts as soon as it is transferred, and happens in parallel with the transfer of the next segment. Likewise, the application of an overlay segment to the base VM proceeds in parallel with the decompression of the next

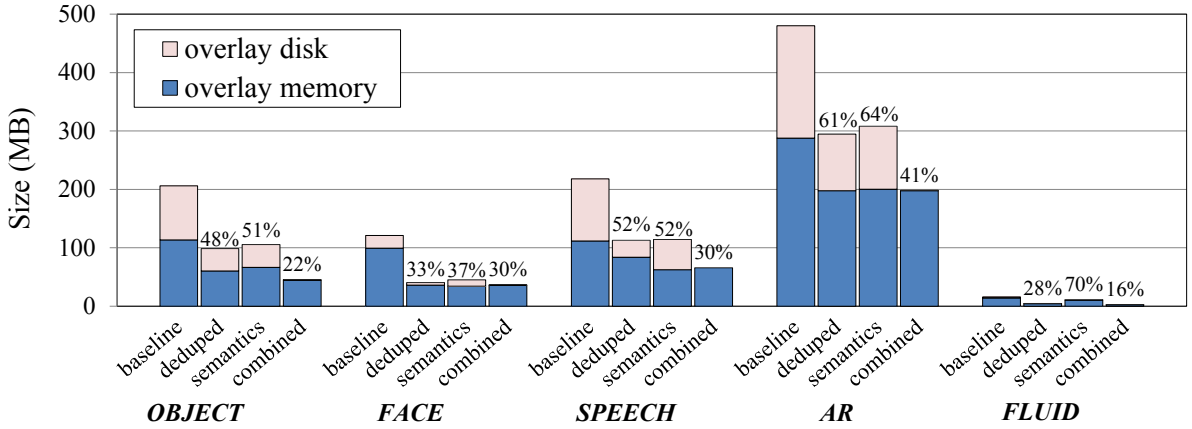


**Figure 6: Overlay Size Compared to Baseline (Percentage represents relative overlay size compared to baseline)**


**Figure 7: Baseline VM Synthesis**

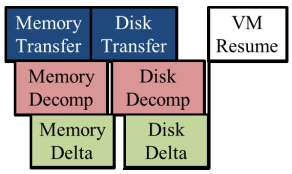


**Figure 8: Pipelined VM Synthesis**

segment. Given sufficiently small segment size, the total time will approach that of the bottleneck step (typically the transfer time), plus any serial steps such as VM instance creation and launch.

## 6.3 Evaluation

Figure 9 compares the performance of the baseline synthesis approach to an optimized one that combines deduplication, semantic gap closing, and pipelining. The results confirm that once pipelining is introduced, transfer time becomes the dominant contributor to the total synthesis time. The synthesis time shown in Figure 9 includes all of the time needed to get the VM to the point where it is fully resumed and ready to accept offload requests from the mobile device. Two applications now launch within 10 seconds (FACE and FLUID), while two others launch within 15 seconds (OBJECT and SPEECH). Only AR takes much longer (44 seconds), but this is because its overlay size and, therefore, transfer time remains high. On average, we observe a 3x–5x speedup compared to the baseline VM synthesis approach from Section 3.

# 7. EARLY START

## 7.1 Concept

We have shown that the optimizations described in the previous sections greatly reduce the size of overlays and streamline their transfer and processing. For several of the applications, the optimized overlay size is close to the size of the install image. Hence, there is little scope for further reducing size to improve launch times. Instead, we consider whether one really needs to transfer the entire overlay before launching the VM instance. This may not be necessary for a number of reasons. For example, during the overlay creation process, the guest OS was already booted up and the application was already launched at the point when the VM was suspended. Any state that is used only during guest boot-up or application initialization will not be needed again. As another example, some VM state may only be accessed during exception handling or other rare events and are unlikely to be accessed immediately after VM instance creation.

| | OBJECT | FACE | SPEECH | AR | FLUID |
|---|---|---|---|---|---|
| % chunks | 17.4 | 56.9 | 26.8 | 65.2 | 27.1 |
| % size | 30.6 | 63.0 | 33.0 | 87.9 | 50.3 |

Percentage of the overlay accessed between VM launch and completion of first request, in terms of chunks and compressed overlay size.

**Table 5: Percentage of Overlay Accessed**

The potential benefits of optimism can be significant. Table 5 shows the percentage of chunks in the overlay that are actually accessed by the five benchmark applications between VM launch and completion of the first request. A substantial number of chunks are not used immediately. We can speed up VM launch by transferring just the needed chunks first, synthesizing only those parts of the launch VM, and then creating the VM instance. The transfer of the missing parts of the overlay and synthesis of the rest of the launch VM can continue in the background until it is completed.

## 7.2 Implementation

We explored a number of alternatives in translating the concept of early start into a viable implementation. One option is to profile the resume of the launch VM, and order the chunks in the overlay accordingly. When offloading, the VM is resumed concurrently with the synthesis operations. If the VM attempts to access chunks that have not yet been synthesized, it will be blocked until the chunk becomes available. If the order of chunks is correct, the VM can begin running significantly before the VM synthesis completes.

Unfortunately, it is difficult to get this order perfectly right. In our early experiments, multiple profiling runs produced slightly different chunk access patterns. In particular a small number of chunks may be accessed early in one run, but not at all in another. With a large number of chunks, it is unlikely that every chunk that is needed early in an actual VM resume will have been picked up in the profiling. More likely, one or more of these chunks will be missed in profiling, and will be placed near the end of the overlay. Getting even one chunk wrong can force the VM to wait for all chunks to be transferred and VM synthesis to complete.

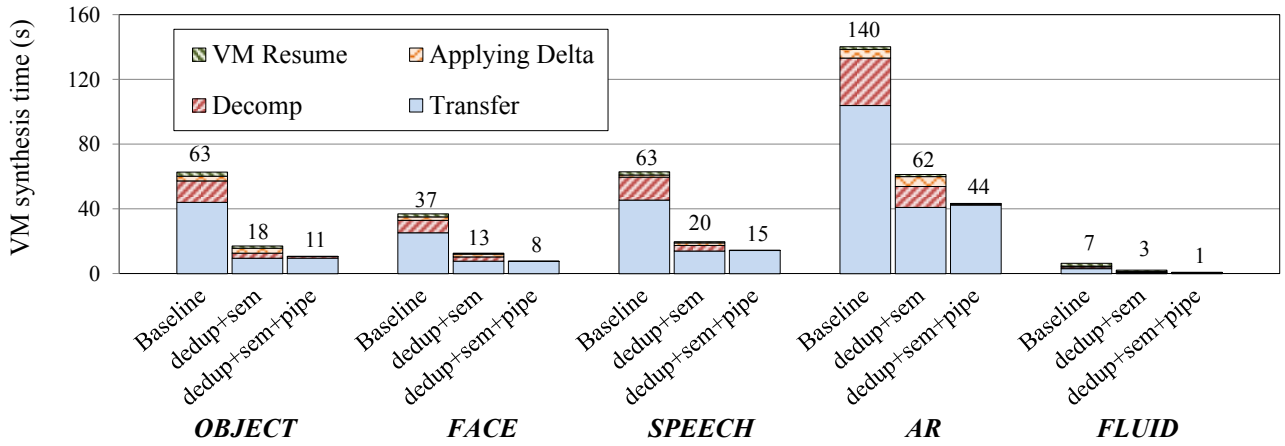


**Figure 9: VM Synthesis Acceleration by Pipelining**

Alternatively, we can avoid trying to predict the chunk access order by using a demand fetching approach, as done in [20], [39], and many subsequent efforts. Here, the VM is started first, and the portions of the overlay needed to synthesize accessed chunks are fetched on demand from the mobile device. Unfortunately, this approach, too, has some issues. Demand fetching individual chunks (which can be very small due to deduplication and delta encoding) requires many small network transfers, with a round trip penalty imposed on each, resulting in poor effective bandwidth and slow transfers. To alleviate this, we can cut the overlay into larger segments comprised of many chunks, and perform demand fetching at segment granularities. This will help amortize the demand fetching costs, but leaves open the question of sizing the segments. Smaller segments let one fetch more closely just the needed chunks. Larger segments, in addition to being more bandwidth friendly, can achieve better compression ratios, but will be less selective in transferring just what is needed. Finally, how chunks are grouped into segments can also significantly influence performance. For example, if needed chunks are randomly distributed among segments, one will likely need to transfer the entire overlay to run the VM.

Our implementation uses a hybrid approach that combines profiling and demand paging, similar to VMTorrent [36] though applied to VM overlays rather than VM images. We make a reasonable attempt to order the chunks according to a profiled access pattern computed offline. We then break the overlay into segments. During offload, we start the VM and begin streaming the segments in order, but also allow out-of-order demand fetches of segments to preempt the original ordering. Thus, we use demand fetching to retrieve chunks that were not predicted by the profiling, but unlike [36], we simultaneously bulk-stream segments in a work-conserving manner to quickly transfer and synthesize all chunks. While this approach bears some resemblance to classic prefetching with out-of-band handling of demand misses, these concepts are being applied to an overlay rather than a VM image.

Figure 10 illustrates our implementation of this hybrid approach. A critical issue is that all of the widely used VMMs, including KVM, Xen, VirtualBox, and VMware, require the entire memory snapshot before resuming a VM, hindering early start. So, we first modify the VMM (KVM in our case) to resume a VM without first reading in the entire memory snapshot. Rather, it now memory maps the snapshot file, so portions are implicitly loaded when accessed. We then implement a FUSE file system that hosts the VM disk image and memory snapshot. This routes disk accesses of the VMM to our user-level code that can perform just-in-time VM synthesis on the accessed chunks (disk or memory). Our code consults

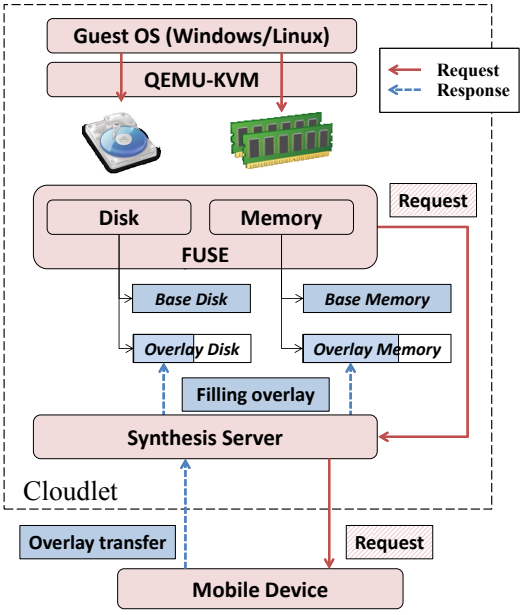


**Figure 10: System Implementation for Early Start**

a small bitmap that indicates whether the particular chunk needs to be served from the base image or the overlay. If the overlay is needed, then a local cache of processed chunks is checked. If the chunk is not available, a demand-fetch of the needed overlay segment is issued to the mobile device. Concurrently, in the background, the code processes the stream of overlay segments as it is received from the mobile device. With this implementation, only the small bitmap assigning chunks to overlay or base image needs to be transferred before the VM is launched.

## 7.3 Evaluation

We evaluate our early start approach with a few different combinations of segment size and chunk order. We test with small (approx. 64KB) and medium (approx. 1MB) sized segments, as well as with just a single segment comprising the entire overlay. (The latter effectively disables demand-fetching). We also test with chunks sorted by access-order (based on a single profiling run of each application) and offset-order (with memory before disk chunks). We slightly modify the ordering so that duplicate chunks are contained within the same segment, avoiding any need for pointer-chasing between segments when handling deduplication.

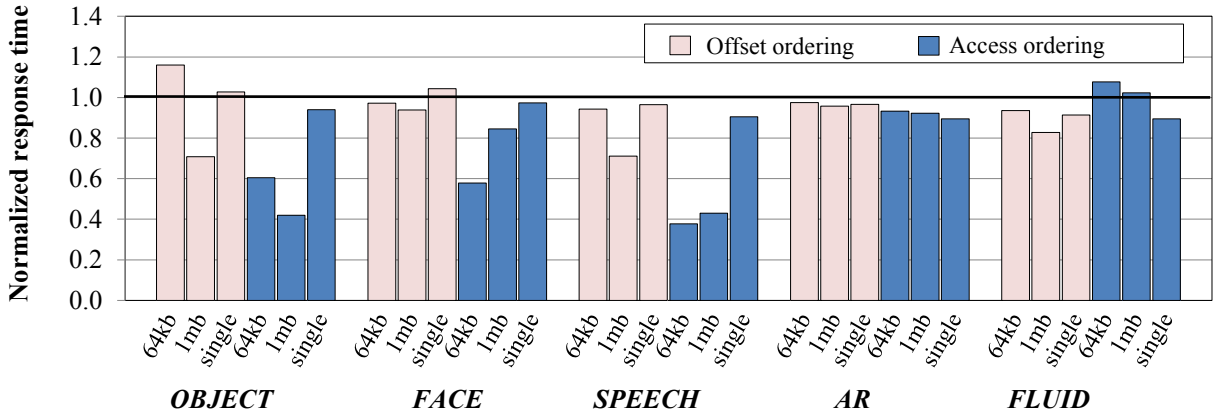


**Figure 11: Normalized First Response Time for Early start**

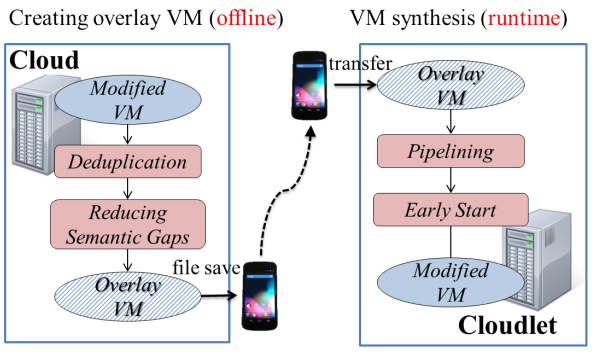


**Figure 12: Fully Optimized VM Synthesis**

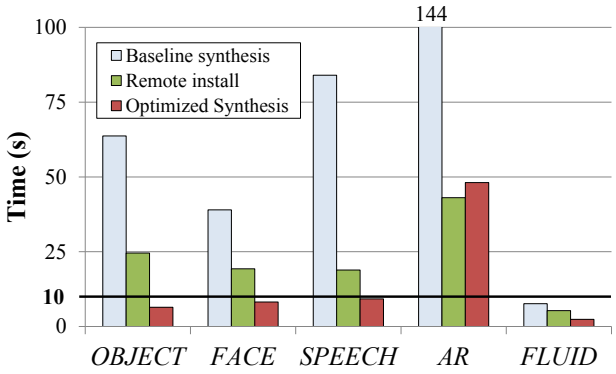


**Figure 13: First response times**

With early-start, the VM synthesis time itself is less relevant. Rather, the metric we use is the first response time of the application. This is measured by having the mobile device initiate the synthesis of the application VM, and then repeatedly attempt to send it queries. The response time is measured from the initial VM start request to when the first reply returns to the client, thus including the overlapped transfer time, synthesis time, and application execution time. Figure 11 compares performance of early start for different chunk ordering policies and segment sizes. The values are normalized to the first response time when the VM begins execution once VM synthesis (including all of the other optimizations discussed previously) completes. Access ordering alone does not help significantly due to the inaccuracies of the single profiling runs. However, access-ordered chunks with demand fetching with 64 KB or 1 MB segments can significantly reduce first response times. We see up to 60% reduction for *SPEECH* and *OBJECT*. For *FLUID*, the response time without early start is already so short that small fluctuations due to compression and network affect the normalized response time adversely. *AR*, which requires 90% of the data in its overlay, does not benefit much from early start.

# 8. FINAL RESULTS AND DISCUSSIONS

## 8.1 Fully Optimized VM Synthesis

We have shown that all of the various techniques for improving VM synthesis described in this paper work quite well on their own. One may wonder: how effective are these techniques when combined? In this section we evaluate a complete, fully-optimized implementation of VM synthesis incorporating all of the improvements described in this paper. The figure of merit here is the total latency as perceived by the user, from the beginning of the application offload process to when the first reply is returned. This first response metric is dependent on the time consumed by the offloading operation and launch of the application VM.

Figure 12 illustrates the fully-optimized process of VM synthesis as we intend it to be used with mobile devices and cloudlet infrastructure. We first construct minimal application overlays via deduplication and by preserving only the semantically meaningful chunks. We store and serve these overlays to the cloudlet from the mobile device (a netbook in our experiments). To minimize the time required to perform VM synthesis, we pipelined the synthesis steps, and then applied early start on the cloudlet.

Figure 13 shows the improvement in first-response times with our fully-optimized VM synthesis over the baseline version described in Section 3. In this experiment, we used an overlay segment size of 1 MB, which provides a good tradeoff between demand fetch granularity and good compression. Overall, we improved performance of VM synthesis by a factor of 3 to 8 across these applications. Except for *AR*, the first responses for all of the other applications come within 10 s. A combination of multiple factors causes significantly longer synthesis times for the *AR* application. First, it has the largest installation size among all five applications and a significant portion of the installation is a database file that is less likely to be deduplicated. In addition, we could not close the memory semantic gap for *AR* since our implementation cannot determine free memory pages for Windows guests. Further, as depicted in Table 5, *AR* requires almost all of the overlay to serve the initial request, and, thus, it does not benefit from the early start optimization.

We also compare our results to the first-response time for a remote installation approach to running a custom VM image. This

1. Create a new EC2 VM instance from an existing Amazon VM image,
2. Attach a cloud block device with VM synthesis tools and base VM image,
3. Change the root file system of the instance to the attached block device,
4. Perform **VM synthesis** over the WAN to construct the modified VM disk,
5. Mount the modified VM disk,
6. Synchronize / copy the modified file system with the instance's original,
7. Detach block device,
8. Reboot with the customized file system.

**Figure 14: Steps in VM Synthesis for EC2**

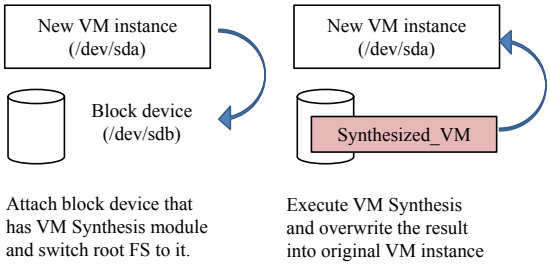


**Figure 15: VM Synthesis for EC2**

involves resuming a standard VM, uploading and installing the application packages, and then executing the custom applications. In Section 3.2, we have already dismissed this approach on qualitative grounds; in particular, even scripted install can be fragile, the resulting configuration is not identical every time, and the application is restarted every time so execution state is not preserved. The only redeeming quality of this approach is that the install packages tend to be smaller than the baseline VM overlays, potentially making the remote install faster. Here, we use highly optimized application packages that are self-contained (including needed libraries, or statically-compiled binaries), and fully-scripted installation to show the remote install approach at its fastest.

As we can see from Figure 13, however, our optimized VM synthesis approach produces significantly better first-response times than remote install in all but one case. In that case, the two approaches are basically a tie. Thus, our optimized VM synthesis approach can achieve very fast offload and execution of custom application VMs on cloudlets, yet maintain strong guarantees on their reconstructed state.

## 8.2 Improved WiFi Bandwidth

All of the experiments in this paper were conducted using 802.11n WiFi at 2.4 GHz (38 Mbps measured average bandwidth). We expect these times to improve in the future as new wireless technologies and network optimizations are introduced, increasing the bandwidth of WiFi networks. In other words, VM synthesis time is now directly correlated to network bandwidth. While WAN bandwidth improvements require large infrastructure changes, mobile bandwidth to the wireless AP at a cloudlet only requires localized hardware and software changes. New WiFi standards such as 802.11ac promise up to 500 Mbps and are actively being deployed [55]. Recent research [14] also demonstrates methods of increasing bandwidth up to 700% with software-level changes for WiFi networks facing contention. Thus, both industry and research are focused on increasing WiFi bandwidth. This directly translates into faster VM synthesis. Based on our measurements, until actual transfer times improve by 3x, the transfer stage will remain the bottleneck (assuming the cloudlet processor remains constant). Beyond this, we will need to parallelize the decompression and overlay application stages across multiple cores to benefit from further improvements in network bandwidth.

| | 10 Mbps | | 100 Mbps | |
|---|---|---|---|---|
| | Synthesis | Amazon | Synthesis | Amazon |
| Synthesis Setup | 44 s | — | 46 s | — |
| Uploading† | 36 s | 607 s | 8 s | 204 s |
| Post-processing | 96 s | 139 s | 97 s | 105 s |
| Total | 180 s | 746 s | 154 s | 310 s |

†Upload time for VM synthesis includes all synthesis steps (overlay transfer, decompression, and applying delta).

**Table 6: Time for Instantiating Custom VM at Amazon EC2**

# 9. VM SYNTHESIS ON AMAZON EC2

In this paper, we have presented VM synthesis as a technique to rapidly offload customized application VMs to cloudlet infrastructure near a mobile device. However, the technique is much more general than this, and can help whenever one wishes to transfer VM state across a bottleneck network. In particular, VM synthesis can significantly speed up the upload and launch of a custom VM on commercial cloud services across a WAN. Here, we describe our VM synthesis solution for Amazon's public EC2 cloud.

The normal cloud workflow to launch a customized VM involves three steps: (1) construct the VM image, including installing custom software and libraries, and making requisite configuration changes; (2) upload the VM image to the cloud, a step largely limited by the client-to-cloud bandwidth; and (3) launch and execute a VM instance based on the uploaded VM image, a step that depends on the cloud provider's backend scheduling and resources. VM synthesis promises to speed up the second step by reducing the amount of state uploaded to a cloud.

Today, no cloud supports VM synthesis as a primitive operation. In our EC2 implementation, we perform VM synthesis entirely within a running VM instance. EC2 does not allow external access to the disk or memory image of an instance, so we cannot manipulate the saved state of a paused instance to effect synthesis. We also cannot generate a data file, treat it as a VM image, and launch an instance based on it. We work around these limitations by performing VM synthesis within a live instance, which modifies its own state and then reboots into the custom VM environment. Assuming that the base VM image and synthesis tools have already been installed in an EC2 block device, synthesis proceeds in the eight steps shown in Figure 14. Steps 1-3 occur on the left hand side of Figure 15, while steps 4-8 occur on the right hand side. We do not handle the memory portion of a VM in EC2 because we do not have access to the raw memory image. This requires an unnecessary reboot and wasted time in synchronizing file systems. If EC2 had a VM synthesis primitive, the memory image and VM disk could be directly exposed by their infrastructure and only step 4 would remain; the VM overlay would be transmitted, applied, and then the VM could be directly resumed without reboot.

We compare the time it takes to perform VM synthesis to the time required in the normal cloud workflow to deploy and execute a custom VM with the OBJECT application. The results are shown in Table 6. For VM synthesis, synthesis setup corresponds to steps 1-3, uploading to step 4, and post-processing corresponds to steps 5-8. With the normal Amazon workflow, there is no analog to synthesis setup. However, after upload, Amazon takes time to provision resources and to boot a VM within EC2; this is included in the total post-processing time. We present results for two WAN bandwidths, 10 Mbps and 100 Mbps, in Table 6. In both cases, VM synthesis wins over the normal cloud workflow with a 4x improvement in the 10 Mbps case and a 2x improvement in the 100 Mbps case. The normal cloud workflow is bottlenecked on bandwidth because it must upload the full 514 MB compressed VM image, but VM synthesis reduces this to a much more compact 42 MB VM over-

lay. It is important to note here that pre- and post-processing for VM synthesis are artificially inflated because of the lack of native VM synthesis support and the convoluted mechanisms we needed to employ to work around limitations imposed by EC2.

# 10. RELATED WORK

Offloading computation has a long history in mobile computing, especially to improve application performance and battery life [11, 31, 38]. The broader concept of cyber foraging, or "living off the land" by leveraging nearby computational and data storage resources, was first articulated in 2001 [41]. In that work, the proximity of the helper resources, known as "surrogates," to the mobile device was intuitively assumed, but how to provision them was left as future work. Since then, different aspects of cyber foraging have been explored by a number of researchers. Some of these efforts have looked at the tradeoffs between different goals such as execution speed and energy usage based on adaptive resource-based decisions on local versus remote execution [9, 10]. Other efforts have looked at the problem of estimating resource usage of a future operation based on past observations, and used this estimate to pick the optimal execution site and fidelity setting [15, 29]. Many researchers have explored the partitioning of applications between local and remote execution, along with language-level and runtime tools to support this partitioning [1, 5, 7].

Since 2008, offloading computation from a mobile device over the Internet to a cloud computing service such as Amazon EC2 [45] has become possible. But, cloud computing places surrogates far away across a multi-hop WAN rather than nearby on a single-hop WLAN. A 2009 position paper [42] introduced VM-based surrogate infrastructure called "cloudlets." Proximity of offload infrastructure was deemed essential for deeply immersive applications where crisp interactive response requires end-to-end latency to be as low as possible. Recent application studies [6, 16] have confirmed the need for proximity of offload infrastructure when a mobile device runs interactive and resource intensive applications.

Aspects of the VM overlay concept can be seen in copy-on-write (COW) mechanisms. Sapuntzakis et al. [39] showed how COW could be applied hierarchically to VMs to create an efficient representation of a family of virtual appliances. Their following work, the Collective [3], advanced this approach and proposed a cache-based system to cope with various network conditions. Similarly, QCOW2, a widely used virtual disk file format, uses a read-only base image and stores modified data in a separate file [25]. Strata [34] combined union file system and package management semantics to easily create and deploy virtual appliances and to dynamically compose them. VM overlays, as articulated in [42], extend the base and modifications concept to both VM disk and memory state, and focuses on a mobile, cyber-foraging use case.

Some aspects of the optimization techniques proposed in this work have been individually investigated in other domains. Deduplication has been widely adopted in file systems, network storage, and virtualization. In file systems, it is used to reclaim storage space by detecting duplicated files or blocks. LBFS (Low Bandwidth File System) [27] is an example of a network file system that uses deduplication to reduce bandwidth demand. It introduced the use of Rabin fingerprints for defining content-based chunk boundaries that are edit-resistant. REBL (Redundancy Elimination at the Block Level) [22] applied deduplication along with compression and delta-encoding to achieve effective storage reduction. It introduced the concept of super-fingerprints to reduce the computational effort of deduplication. Deduplication has also been used in the virtual machine space. Waldspurger removed duplicated memory pages and shared identical memory pages across multiple virtual machines to conserve memory on the host machine [53]. Several recent works have also used deduplication to reduce the cost of VM migration both within datacenters [57] and across WANs [56]. As our work uses deduplication in an offline stage, we can apply it aggressively across both disk and memory images.

Demand fetching of VM disk state was introduced by Kozuch et al. [20] and Sapuntzakis et al. [39]. Both leveraged the fact that only a small portion of a VM disk is typically accessed in a session. Post-copy migration [17] applied demand fetching of VM memory to live VM migration to reduce network transmission costs and the total migration time. Post-copy migration immediately started the VM at the target destination instead of pre-copying a VM's memory state over mulitiple iterations. SnowFlock [23] combined demand fetching and packet multicasting to provide highly efficient and scalable cloning of VMs. It started VM execution on a remote site with only critical metadata and performed memory-on-demand, where clones lazily fetch portions of VM state as it is accessed. VM image Distribution Network (VDN) [33] used demand fetching of content-addressed chunks in the datacenter. VMTorrent [36] enabled scalable VM disk streaming by combining block prioritization, profile-based execution prefetch, and on-demand fetch. Our work also uses profiled prefetching and demand-fetching.

The significance of the semantic gap between VMMs and guest OSes was first articulated by Chen and Noble [4]. Later, Garfinkel and Rosenblum [13] coined the term virtual machine introspection and developed an architecture focusing on analyzing memory. Another effort to bridge this gap is VMWatcher [18], which enabled malware detection by introducing a technique called guest view casting to systematically reconstruct internal semantic views of a VM, such as files, processes, and kernel modules, in a non-intrusive manner. Kaleidoscope [2] exploited x86 architectural information (e.g. page table entries) to classify VM memory into sets of semantically-related regions and used this for better prefetching and faster cloning of a VM into many transient fractional workers. Our work bridges the semantic gap to minimize VM overlay size by identifying freed pages and blocks, and, to the best of our knowledge, is the first to use TRIM support for this purpose.

# 11. FUTURE WORK

Our experiments used a netbook as a surrogate for a powerful mobile device of the future. Although we expect hardware specifications of smartphones will soon catch up with today's netbooks, we plan to repeat our experiments on an Android-based smartphone to verify the feasibility of our optimizations on these platforms. We do not anticipate major differences in the results, since most of the processing in our system is done offline or on the cloudlet, and the mobile device mostly acts as a sensing, user interaction, and data storage device.

We also plan to re-engineer our software as an extension to the widely used OpenStack platform for cloud computing. With this in mind, we have carefully designed and implemented our system to support backward compatibility with OpenStack. Acceptance of our code into OpenStack would simplify the deployment and widespread use of VM synthesis, especially since some of our optimizations require modifications to KVM.

An important aspect of practical cloudlet usage is leveraging temporal locality of user mobility. In daily life, most users are likely to follow repeated routines and to frequently revisit a few locations. Hence, there is high value in caching the results of previous VM synthesis operations. By reusing cached launch VMs, the synthesis step can be completely avoided. This can be especially valuable if the overlay is large.

## 12. CONCLUSION

Beyond today's familiar desktop, laptop and smartphone applications is a new genre of software seamlessly augmenting human perception and cognition. Supporting the compute-intensive and latency-sensitive applications typical of this genre requires the ability to offload computation from mobile devices to widely dispersed cloud infrastructure, a.k.a., cloudlets. Physical dispersion of cloudlets makes their provisioning a challenge. In this paper, we have shown how cloudlets can be rapidly and precisely provisioned by a mobile device to meet its exact needs just before use. We have also shown that although our solution, dynamic VM synthesis, was inspired by the specific demands of mobile computing, it also has broader relevance to public cloud computing infrastructure.

We have made our source code available for download at our project site: `http://elijah.cs.cmu.edu/`.

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