**Packaging and streaming assets to decrease the memory footprint in video games**

Jarryd Hall, Taher Odeh

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**ABSTRACT**

Memory related issues such as memory management, limited memory and memory related application crashes, etc. often affect video games. Private game development companies have created the previous solutions to these kinds of issues and there are no open source solutions available for developers to utilize. This paper presents a constructive research approach to solving these memory issues. Operating systems were studied in order to properly understand these memory related issues and determine a viable solution. The solution needed to be implemented in such a way that multiple platforms could be targeted, although for the scope of this paper the focus was on iOS and Mac OSX. The solution

**General Terms**

video games, memory management, virtual memory, cross-platform, game performance, optimization

**Keywords**

virtual memory, mmap, Packaging tool, API, compression, caching, RAM, HDD, memory enhancement, file-system

# 1. INTRODUCTION

Almost all video games are bound by memory constraints. The system running the game can only allocate a certain amount of usable memory for the game’s process and this is usually less than advanced games need. The system’s kernel running the game will allocate memory for the game on RAM as well as on the HDD, which is where the virtual memory is located, and often the assets and game resources are very large, consuming a lot of the available memory.  
  
These memory constraints effects game developers and designers working within the development process of a project.

There are techniques used to solve this memory issue, but they are privately owned and with little documentation surrounding how the memory problems are solved. This study sets out to solve the issue and implements an open source solution so that indie game developers who are not aided by proprietary techniques can create better games. Implementing a solution for this problem and licensing it as open source will allow anyone to be able to increase game performance as well as improve the overall game design and development.  
  
The problem above was pointed out during an initial interview with Johan Knutzen, the founder of Senri and Phobic-Games, mobile application and game development companies based in Gothenburg, Sweden, which are strongly involved in this research paper and it’s requirements and solutions.

The solution that was developed included a number of elements. The packaging tool compresses all the assets for a game into a single pak file. The pak file format is a file format that contains archived data, which is either compressed or decompressed. The API allows developers to use the generated pak file, as well as handles the memory optimization.

In order to test the developed solution, a sample game was run numerous times with and without the solution present. The game was profiled and monitored for memory and performance variables and the data was compared.

The question researched in this paper was:

* How can the memory footprint of video games be decreased?

# 2. Related Work

The literature on the subject of utilizing virtual memory to enhance memory on a gaming system is limited because the concept is usually developed for AAA video games. ID Software has done the most notable implementation using a similar concept. John Carmack is the lead developer for ID Software and discusses how he used memory mapping to enhance the game.(add reference to this here <http://www.bethblog.com/2010/10/29/john-carmack-discusses-rage-on-iphoneipadipod-touch/>)

CRAMES is a system to enhance memory on embedded systems. (Add reference here to CRAMES paper) Compressed RAM for Embedded Systems uses efficient algorithms as a RAM compression technique.

“CRAMES takes advantage of an operating system’s vir- tual memory infrastructure by storing swapped-out pages in com- pressed format. It dynamically adjusts the size of the compressed RAM area, protecting applications capable of running without it from performance or energy consumption penalties. In addition to compressing working data sets, CRAMES also enables efficient in-RAM filesystem compression, thereby further increasing RAM capacity.” (add reference to CRAMES paper)

CRAMES uses a filesystem for compressed data segments in RAM and targets low-power embedded systems.

The paper on CRAMES (reference paper here) also acknowledges “Cramfs”, acronym for cram a filesystem onto a small ROM. Cramfs (add reference to https://github.com/wendal/cramfs) is a compression library to compress files to be used on ROMs. It uses zlib to compress one page at a time and allows random access to these pages. Cramfs targets systems , which have a maximum filesystem size of 256MB. (add reference <https://github.com/wendal/cramfs>)

CRAMES works on a lower level than the target of Bundle. CRAMES registers itself with the kernel as a memory block and offers a function by which the kernel can access the compressed data whenever there is a read or a write operation. (add reference to CRAMES paper) Both of these mentioned systems use compression of file systems themselves and target small memory systems.

File formats are well-researched topic as they form a core of the way computer systems work. The Pak file is a file that is packaged with many files and works as an archived file. Games such as Quake (add more games here and reference) use pak files as a means of holding game data files in an archived manner. The pak file serves as a means to hide asset data files from extraction as the game assets are archived into a single file and not left inside a resource folder.

# 3. Constructive Research Method

The method used in this research is the Constructive Research Method. Crnkovic, (2009) describes this method as a way to turn existing knowledge into novelty or innovation by implementing a solution, to an existing problem, whether it is theoretical or practical, as long as it involves the usage of preexisting knowledge and thinking to produce artifact design solutions, for example, plans, diagrams, charts or software implementation; it may be considered constructive.

In addition to the description above, Kasanen, et al. (1991) summarizes this method as a solution oriented method where innovative step-by-step solutions are taken into account, followed by testing of the solution and using the data within the testing phase for analysis purposes.

Lindholm (2008), provided three category examples of knowledge gaps to be filled using the constructive research method: feasibility, where a solution to a common problem has not been done yet; Novelty, where a unique and new solution is provided to an already solved problem; or an improvement, where the goal of the research focuses on a preexisting solution and aims to produce better results than the ones available.

The method mentioned has been found the most suitable for this research, basing on the fact that the latter aims to cover a feasible constructivism in terms of finance and freedom by having the solution free of charge and also freely licensed. Additionally, Caplinskas (2004) argues that the constructive research method befits the computer science and the IT related problems in a usual manner.

The constructive research methodology allows for qualitative and quantitative approaches to be mixed or used as needed depending on the kind of data to be gathered during the development process of the solution.

There are crucial steps to be followed to order to conduct a constructive research (Lindholm, 2008):

1. Finding a research worthy problem.
2. Considering the potential of enlarging the research to become a project.
3. Obtaining a detailed understanding of the topic researched.
4. Constructing a theoretical solution.
5. Implementing a practical solution and test its usefulness.
6. Examining the applicability of the solution.
7. Showing the theoretical connection and the solution’s contribution.

[Prove why its possible to minize steps to 4]

The theoretical steps above have been modified to best fit a framework that shall provide more relevancy to the process of solving the problem. The framework consists of 4 phases; In the first phase, a problem is discovered, and the research runs towards understanding of key topics surrounding the problem and finding theoretical solutions; This phase includes and combines the first 3 steps; In the second phase a practical constructive solution is conducted and the implementation of the product starts, thus making use of steps 4 and 5; The third phase tests the implemented solutions, covering steps 5 and 6. And in finally phase 4 a demonstration of the product is ran, showing numerical differences in efficiency in order to bold out the solution’s contribution mentioned in step 7. (See figure 1)

In each phase qualitative data collection and analysis methods were used to gather information about the problem relevant to the considered requirements/tasks of that phase. In addition to a quantitative data-collection and analysis approach used within the testing phase.

**Data Colletion:**

Qualitative:

Quantitative

Qualitative methods were used to gather information that was needed to construct the solution. Open discussions were had with a stakeholder on an as-needed basis. These discussions were more suited than interviews as no time was wasted on establishing the focus of them. Discussing ideas and possible solutions to the current tasks at hand, allowed for a more streamlined iterative development process. These discussions also saved valuable development time as analysis was not done on interview or survey gathered data. The discussions dynamically led to focused, implementable solutions for the task at hand.

The process used can be shown with the following diagram:

ADD DIAGRAM HERE>

# 4. Bundle

The solution developed was planned from the start to be an open source project (add reference to github here), releasing the product under a Bsd License or similar (add reference to Bsd License here). The reason for this decision was the fact that memory management is something every game developer has to deal with and offering an open source solution could help other developers and possibly gain the interest of the game developers community and evolve the project. The focus of Bundle is to target as many platforms as possible because games run a wide range of systems. The focus of this research paper is on the iOS and Mac OSX platforms, although the code itself is C, which allows multiplatform support.

Understanding how the current hardware and software operating systems work was crucial in developing Bundle. Game developers can encounter various bugs and issues related to their memory management.

Memory also highly effects performance of games especially on mobile devices where the available hardware resources are limited.

These negative effects can impact a game development cycle in devastating ways.

These effects could range from longer development cycles due to bug fixing and memory management to the far worse scenario of decreasing game asset quality to reduce RAM footprint. The development cycle is usually guided by budget and cost, and especially within indie projects and smaller game development project, the budget could force drastic changes to be made to the project.

Bundle can aid game development projects that are already at that point in a project or any other time during the development phase. Developers can import and use it from the start of a project or integrate it during development.

Bundle works by compressing a game’s assets by filename into a single archived file. The file is then loaded into virtual memory using the Bundle API. The files within the archived file are then accessible using the filename itself. The file is retrieved and returned to the game process as a range of bytes, using a pointer and a file size variable.

These memory issues are experienced with manually allocated memory in RAM. A system also allocates a block of virtual memory to a process. Virtual memory resides on disk and acts similar to a swap file.(add swap file reference here).

The storage of memory on disk and using this virtual memory during a game’s process is especially important on devices using Solid State Drives. Solid State Drives work similar to RAM. Solid State Drives have lower access times and lower latency than older hard drives. (add SSD reference here)

Mobile devices such as the iPhone and iPad, which run iOS, have Solid State Drives. This is a reason why they were chosen as the target of this papers research. Solid State Drives thus allow faster access to the virtual memory mapped files as compared to traditional hard drives.

Once the file is mapped to virtual memory the addresses are translated as the data is paged in from virtual memory.

ADD info here about Paging etc.

A MMU(add MMU reference here) is used by the CPU to translate virtual memory addresses.

As Apple’s iOS and OSX platforms were the focus of this research, the memory management was researched on Apple’s self- published documentation.

The kernel manages RAM and Virtual Memory segments. When an application launches the kernel allocates a block of memory in RAM, e.g. around 40MB on the iPhone 4 and also assigns a virtual memory data segment, e.g. around 700MB on the iPhone 4. (add profiling diagrams? Or some reference). The RAM and Virtual Memory work together by means of paging data segments or pages, in and out, between each other. When a data segment is needed that resides in virtual memory, the kernel pages in the page that holds that data into RAM. (add virtual memory reference to apple’s site here) . Data is paged into RAM from virtual memory until the calculated max RAM size is reached. Once this occurs the kernel will page out data that is not currently needed, and replace it with the page from virtual memory that holds the currently needed data.

Virtual memory became the focus at this point to be the basis of the solution. Data allocated to virtual memory rather than strictly allocated to RAM using objective C’s alloc method would allow larger segments of data to be allocated due to the size of the virtual memories data block, e.g. around 700MB on iPhone 4, compared to the iPhone 4’s 40MB RAM.

A POSIX function called mmap (reference mmap here) is a low-level virtual memory mapping technique that allows one to allocate a file on disk into virtual memory addresses.

As mmap could map a file to virtual memory for use within a running process, creating a file for a game’s assets became the focus at this point.

# 5. Bundle Design

Video games can run on many different platforms so targeting as many platforms as possible was a design decision from early on. Using C to develop Bundle would allow this as it supports multiple platforms. (add reference here to C platform target) C compiles correctly with Objective-C, the language used in iOS and OSX. (add reference to C compiling with obj c)

Integrating Bundle into an existing project or a fresh project has been made as easy as possible for the developers using it. The packaging tool takes a source folder and a destination pak file name, without the need for the pak file to exist beforehand. The tool packages each individual file into the pak file and indexes the file information into the header. (add info about header here and file format design)

The API is a static library that develops can include and use the code. The usage of the API is split into 3 basic functions.

1. int bundle\_start(char \*pakFile, struct mappedData \*mData)
2. offset\_p bundle\_getIndexDataFor(char \*fileName)
3. int bundle\_stop(struct mappedData \*mData)

The bundle\_start function starts Bundle by loading a given pak file, memory mapping the file to virtual memory and returns success or failure.

The bundle\_getIndexDataFor function retrieves the file offset and size for a developer with the ease of only needing a filename as an argument.

The bundle\_stop function stops Bundle by destroying the hash table and removing the mapped file from virtual memory.

A wrapper is also available to developers who need Objective-C specific objects. The function

id bundle\_useFile:(NSString \*) fileName forObject:(id) object

takes a filename and an object pointer as arguments, then retrieves the data from virtual memory using the Bundle API. The retrieved data is then passed to a native function for NSData and creates an object, which the developer can then use to hold their game assets. NSData is an object that holds binary data and can be used as arguments to methods requiring other object types. (add reference to NSData here and also an example maybe of UIImageView using NSData)

ADD diagram here to show how bundle works on a high level.

# 6. Bundle Implementation

## 6.1 Tool and Pak File Creation

The pak file format is an archive file format that is not standardized on its contents. Pak files are usually used for games, where game assets are archived into a single file. (add reference to pak file here) (possibly add info about other games that use this as well as battlefield that uses it for every level, having multiple pak files)

A tool was then developed to archive these game assets into a single pak file. This was created as a command line tool that takes two arguments, the source folder and the output file. The tool takes the source folder, traverses the entire directory to count the files, ignoring DS\_Store files that are present on Apple’s platforms(reference DS\_Store). Once the file count is obtained, the value is used to calculate the variable header length.

The pak file header consists of offsets holding information about the files compressed within the pak, in addition to an integer in the beginning of the file representing the number of files compressed. Each offset in the header holds 20 bytes of information needed to be used to locate files in the archive, the first 4 bytes in an offset holds the hash value of the filename, the next 8 bytes hold the index of the beginning of the data of the that file within the archive, the remaining 8 bytes in an offset hold the size of the that file in bytes. The above information is stored in a binary form in the header of the pak file to allow the data compressed to be located by the filename of the original file.

Each asset within the source folder, e.g. sound files, textures, images etc. is compressed using zlib(reference zlib here) and indexed within the pak file, with its index information stored in the header segment. (reference file format creation link)

The tool outputs a pak file at the user specified destination path. Once this pak file is created it is ready to be used within the application.

## 6.2 The API

The base API was developed in C allowing for future evolution of the product, which is especially needed for an open source project where many people might have ideas to evolve the product.

For the focus of this research paper, the operating systems being Apple’s iOS and Mac OS X, wrapper methods were needed to support Apple’s Objective-C language, which forms the basis of the Cocoa and Cocoa Touch frameworks.(add reference here to objc and cocoa/touch) Objective-C is a superset of C, allowing it to integrate seamlessly.

The wrapper function was only needed to pass the needed data’s pointer, the pointer to the data in virtual memory, to the object needing it within an objective-C runtime environment.

The Objective-C NSData class has a method for passing a pointer to an address as well as the length of bytes to process, with the alternative option of freeing the data when done or not. (add reference here to the NSData class)

+ (id)dataWithBytesNoCopy:(void \*)bytes length:(NSUInteger)length freeWhenDone:(BOOL)freeWhenDone

This allows an object to be created using the virtual memory pointer and size of bytes of the segment, without the need to allocate memory in RAM for the object. This perfectly integrated with the developed base C API that allowed retrieval of a file’s index data within the pak file, using the filename itself. (add a possible function call and small explanation of the process)

This feature would make it as simple as possible for developers to use the API as they can use their filenames as usual without needed an understanding of how the file’s data is passed to the called NSData method.

A hashmap implementation was developed based on khash(C)(add reference) to hold offsets red from the header of the pak file, thus allowing easy and fast access to information about packed files in the archive. The hashmap is initialized globally on the stack and is structured to hold the hash values of the filename (add reference to hashing function) as the key, and the offset copied from the header as the value.

Usability was always an important attribute of the solution as it is an open source project and will hopefully be used my many developers.

The use of the API was minimized to 3 important functions:

* int bundle\_start(char \*pakFile, struct mappedData \*mData)
* offset\_p bundle\_getIndexDataFor(char \*fileName)
* int bundle\_stop(struct mappedData \*mData)

The first starts Bundle by hashing and memory mapping a given pak file. The second function is the one that is always used directly or from within a wrapper method to retrieve the needed data pointer and size, that, if called from a wrapper can be passed to the native languages method. The third function stops Bundle, by destroying the hashmap and unmapping the file from virtual memory. Allowing such ease of use of the Bundle system developers do not need to lose valuable development time, as another important attribute of Bundle is to improve the development process in various ways. Developers can integrate Bundle quickly into existing games.

Add information here about the crossroads we came to with the different options regarding compression and decompression, or will that come in the discussion?

Once the tool was packaging assets correctly into a pak file and the API could correctly place the pak file’s header info into a hashmap and memory map the file to virtual memory, the focus was on reading this data and making it available to the caller. An issue arose regarding what to do with the needed compressed data. The issue was that if a number of compressed files are within the pak file, and mapped to virtual memory, when using this data for objects, the data should be used directly from virtual memory, rather than copying the data temporarily to the stack, whether it was decompressed or not. A number of options were considered.

1. Package the game assets into the pak file without compression.
2. Package the compressed assets into the pak file, and decompress the entire file to virtual memory, re indexing an internal structure.
3. Package the compressed assets into the pak file, and decompress data as needed.
4. Package the compressed assets into the pak file, and decompress and memory map individual files on demand.

All of the above had side effects for the solution such as loading times, decreased memory size, memory fragmentation which would lead to no memory being available of a large enough size for a needed block, even if the total free memory was more than enough. The main issue with the mentioned options was the fact that they all forced a temporary duplicate of the virtual memory mapped data to be placed somewhere else in memory, either the stack or the heap. Keeping with the focus of reducing strictly allocated RAM usage to a minimum, the stack would be the option. If a game had n objects all with their source data memory mapped in virtual memory and a duplicate of the decompressed data in memory, it would not be a solution to a problem as much as it is reading from a file and using the same amount or memory.

This led to a solution where filetypes needed to be defined as to how they are used. Defining which file types needed to be decompressed or not during runtime would allow the most dynamic and efficient way to handle the data for use by objects.

The game assets would be packaged as compressed files into the pak file and when the bundle\_start function is called, the assets filetypes would need to be analyzed and depending on the type, either decompressed into virtual memory or left compressed.

The reason for this is that certain functions or methods that use this data work more efficiently with compressed data; others work more efficiently with uncompressed data.

Give some examples of the file types?

# 7. Discussion & Conclusion

# References:

[ref2 = Kasanen et al. (1991)]

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