Monitoring Memory-Related Software Aging: An Exploratory Study

Rivalino Matias **Bruno Evangelista** **Autran Macedo**

School of Computer Science
Federal University of Uberlândia
Uberlândia MG, Brazil

AGENDA

- Introduction
- Memory Leaking and Software Aging
- Monitoring Aging Effects of Memory Leaks
- Conclusions

Introduction

- Many experimental researches have focused on characterizing the aging phenomenon and evaluating the effectiveness of rejuvenation mechanisms.
- For both cases monitoring aging effects is essential.
- In this work, we investigate important aspects related to monitoring memory-related software aging effects, especially related to memory leaks.

Research Goal

- The correct understanding of software aging is a major requirement to make educated decision and providing reliable system diagnostics.
- Our goal is to present a practical body of knowledge to support the solid understanding of important aspects of monitoring aging effects related to memory leaks.
- As an exploratory study, this work discusses findings that will assist experimenters to choose better strategies for measuring aging effects.

Research Scope

- Software aging effects related to main memory are the most cited in the literature.
- Fundamentally, memory-related aging effects are caused by memory leak or memory fragmentation problems.
  - Memory leak is mainly caused by inadequate use of memory management routines.
  - Memory fragmentation is a consequence of the system operation dynamics.

Research Scope

- Memory fragmentation has gained more attention in the recent software aging studies.
- However, the majority of experimental researches in this field still focusing on memory leaking.
- The accurate detection and measurement of memory leaks are not trivial tasks.
  - it requires a deep understanding on the underlying mechanisms behind this problem.

Memory Leak

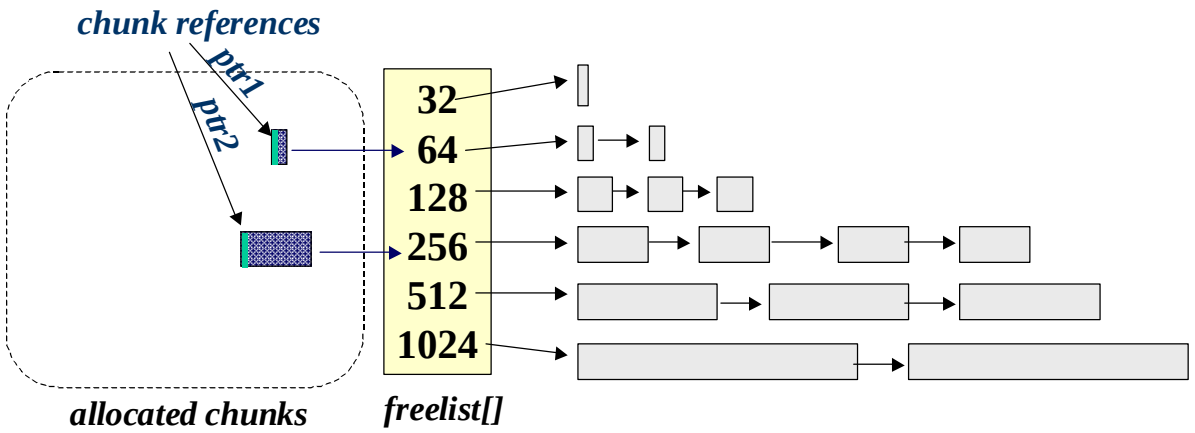
- Memory leaking occurs when the application process does not release previously allocated memory blocks that will not be used anymore.
- There are several reasons for this happen, and we propose to classify them in two main types:
  - **involuntary** and **voluntary** non-releasing of memory.

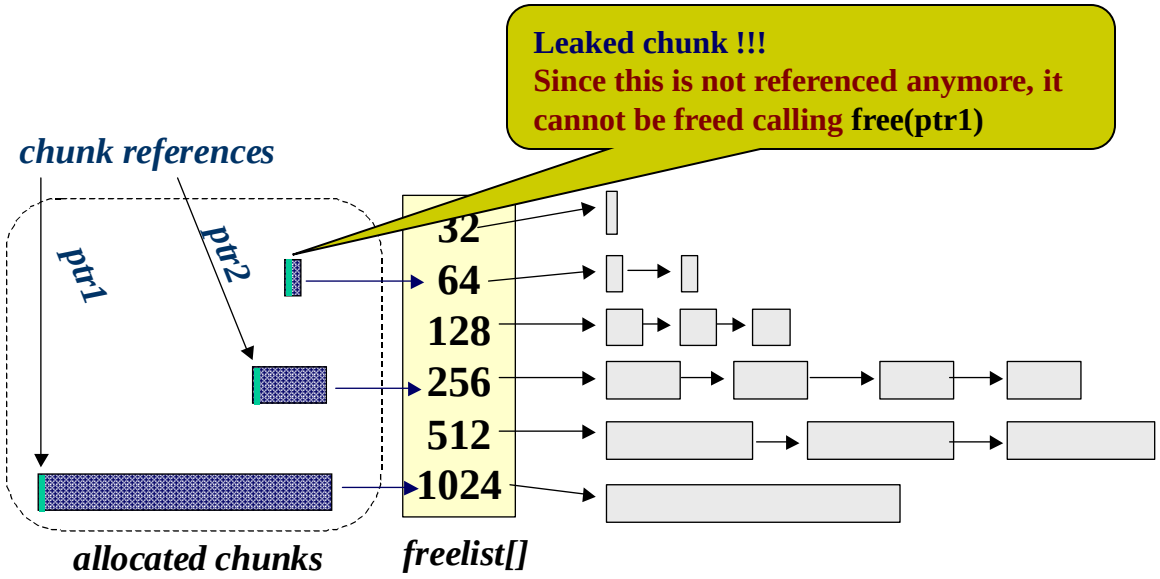
Memory Leak

- **Involuntary** non-releasing of memory occurs when a process is unable to release a previously allocated memory block.
  - it happens mainly due to losing the reference (address) to the allocated block.
  - Another example is the unbalanced use of *malloc* (or *new*) and *free* (or *delete*) routines.

Memory Leak

```
...
ptr1=malloc(60)
ptr2=malloc(250)
...
...
...
...
ptr1=malloc(1000)
```





Memory Leak

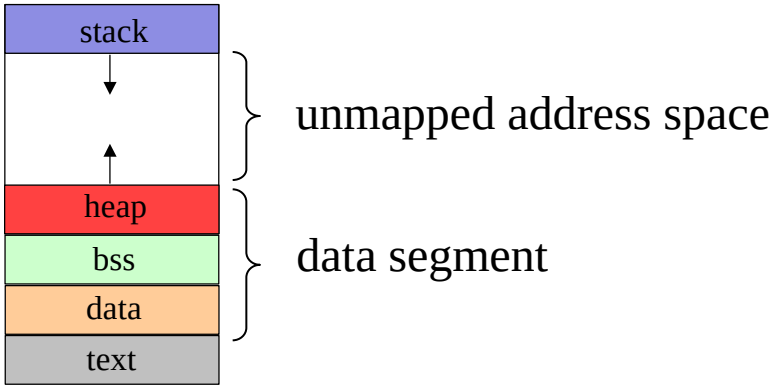
- Voluntary non-releasing of memory is related to the software design.
- In order to improve performance, some applications preallocate pools of memory blocks.
  - to avoid the computing costs of repetitive operations for allocating and releasing memory objects.
  - the size of resource pools usually increases monotonically.
- We can find this *design pattern* in many nowadays server applications

Memory Leak

- The practical result in both situations is the application process gradually consuming more memory during its runtime.
  - in long-term executions this may exhaust the computer main memory.

Memory Leak

- Since the memory leaking causes the heap saturation, additional memory has to be requested to the OS.
- Hence, a new memory area (new heap) is added to the process address space
  - making the process size to grow !



Conclusion #1

- Based on this observation, an important conclusion can be drawn:

whereas the process heap is not enlarged the process size still unchanged, even under occurrences of memory leaks.

Aging Indicators

- Software aging effects can be detected only during the system's runtime.
  - through monitoring aging indicators.
- Aging indicators are variables that represent the stable state of a given system.
  - comparing the monitored aging indicators with standard values for a given system could help to reveal the presence of aging effects.
- The quality of aging indicators affects the effectiveness of rejuvenation mechanisms
  - given that their efficiency depends on the activation time that is influenced by the accuracy of the chosen aging indicators.

Aging Indicators

- Aging indicators can be considered at different system levels:
  - application's components, application's process, middleware, operating system, virtual machine, hypervisor, ...
  - since software aging can occur inside all of these layers, it is important to adopt the appropriate indicators for each layer.
- In general, aging indicators are classified in two categories according to their granularity:
  - **system-wide** and **application-specific**.

System-wide Aging Indicators

- These indicators provide information related to subsystems that are shared and influenced by other system components.
- Examples of shared subsystems
  - Application middleware, operating systems, VMs, and Hypervisors.
- Indicators of this category are used to evaluate the aging effects in the system as a whole.
  - e.g., total free/used memory, free/used swap space, # of open files, # of processes, # of soft interrupts, …

Application-specific Aging Indicators

- These indicators provide specific information about an individual application process.
- Examples of aging indicators in this category are:
  - Process' resident set size (RSS), JVM heap size, and application's response time.
- If the application of interest is not running directly under the OS, but inside of a virtual machine platform, these aging indicators could be applied indirectly, targeting the process running the virtual platform (e.g., Java and C#).

Aging Indicators Monitoring

- For both classes of aging indicators, it is possible to collect data from the user-level and kernel-level.
- Collecting data from user-level is implemented by special-purpose programs that run at the user level.
  - at this level the system-wide monitoring is limited to the information that the OS exports to the user level.
- It is possible to collect data from the kernel level through an instrumented kernel
  - Kernel changes for this purpose can be done either statically or dynamically.

Using System-wide indicators

- They are adequate when there is no previous knowledge of the system under investigation, offering a first overview.
- This is particularly important when working with a new or unknown system and many candidate variables are preliminarily considered.
- Many previous research works in software aging and rejuvenation have used this approach.

Using System-wide indicators

- Due to the shared nature of system-wide indicators, they usually present significant noises.
- Specific on memory leak, the most frequently used system-wide aging indicators have been the free or used main memory.
- Only monitoring these indicators is very hard to make a precise diagnostic if the system suffers or not from memory leaking.

Experiment #1

- We run a workload emulating typical file system operations executed in webserver systems.
- We use the well-known *filebench* workload generator for this purpose.
- We adopted three types of loads:
  - low (w1), moderate (w2), and high (w3).

Experiment #1

Table 1. Workload Profiles (filebench.f)

Profile	Workload Parameters	
w1	#files= 5000	#threads= 25
w2	#files=10000	#threads= 50
w3	#files=20000	#threads=100

- The three workloads are executed twice, in a cyclical way.
- Each run lasts for one hour. Total time per experiment is six hours
- We repeated each experiment 10 times to minimize the experimental errors.
- Thus, the discussed results are based on the averaged values.

Experiment #1

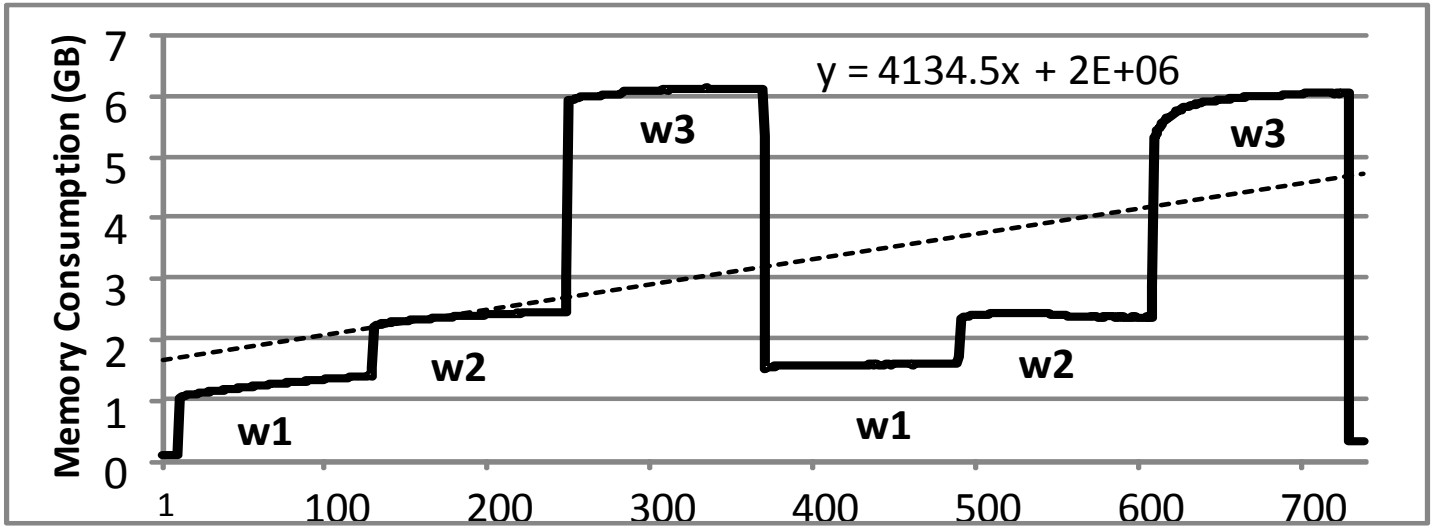


Figure 1. Pattern of increasing memory usage observed in memory leak scenarios.

Experiment #1

- As can be observed, the results indicate an increasing trend in the memory consumption.
- This pattern is frequently observed in experimental tests using system-wide aging indicators (e.g., used physical memory).
- However, analyzing carefully the dataset we note that this trend is not consequence of software aging, but simply the effect of the OS disk cache (so-called *buffer-cache*).

Experiment #1

- Since the adopted workloads are disk I/O-intensives, the OS kernel memory management requests unused physical memory to the page-level allocator in order to create additional disk cache objects.
- This behavior is expected considering that:
  - i) there is free physical memory available in user level, and
  - ii) the disk I/O subsystem is under pressure.

Experiment #1

- In such scenario, it is not uncommon to observe the amount of free memory decaying considerably.
- This behavior may easily be misinterpreted as memory leaking, where in fact we have the available memory being temporarily moved to the OS buffer-cache subsystem.
  - note that the used memory can be made available to the user level again as soon as it is necessary.
- Looking at free/used memory alone or combined with other noisy system-wide aging indicators (e.g., swap space) may lead to erroneous conclusions about memory leaks

Experiment #1

- For cases like this, we suggest to monitor not only the used/free memory, but also comparing it to the memory used in *buffer-cache* and the total memory allocated for the *user-level*.
- These combined analyses will help to understand the memory flow inside the system, and see if leaks are really occurring.
- This approach is especially important to avoid misdiagnosis when using memory-related system-wide aging indicators.

Experiment #1

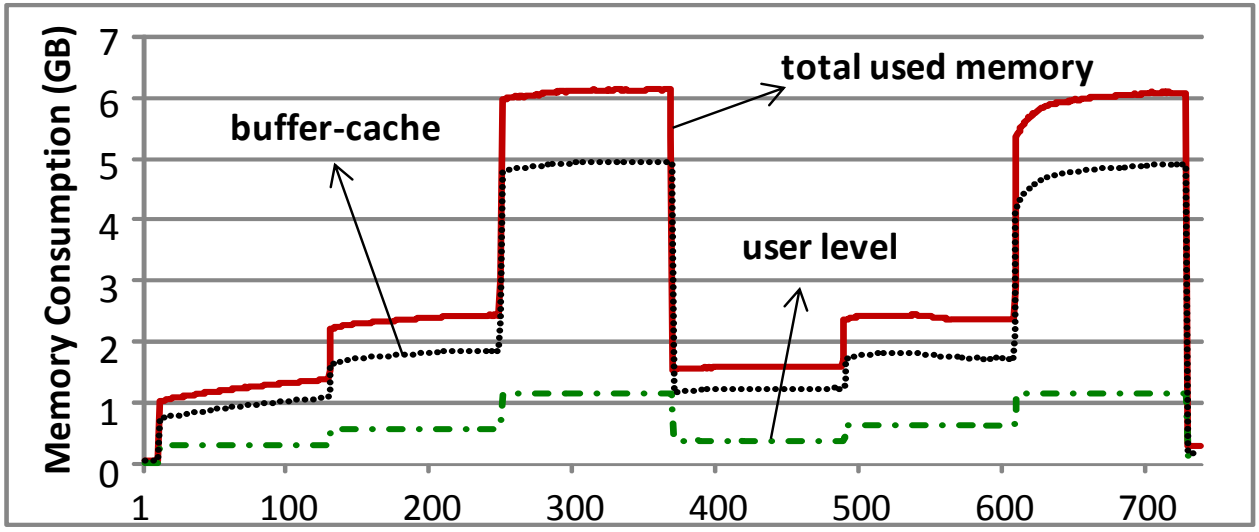


Figure 2. Monitoring combined system-wide memory related aging indicators

Experiment #2

- Preferentially, for well-known systems we recommend to compare the values of aging indicators with a baseline known to be aging free.
- To illustrate this we conduct a second experiment.
- In Exp. #2 we execute an application process along with the workload used in Exp. #1 running in background.
- Exp. #2 is composed of four tests (#2.1 – #2.4).

Experiment #2

- In #2.1 we monitor the total used memory while running a leak-free application (our baseline).
- In #2.2 we inject random memory leaks only in application level.
- In #2.3 we inject random memory leaks only in kernel level.
  - through a faulty kernel module.
- In #2.4 we inject memory leaks in both application and kernel levels simultaneously.

Experiment #2

Algorithm 1. No memory leaking

t: sleep time in seconds
f: multiple of page size
loop
    t = **random** (1..30);
    f = **random** (1..5);
    c = **malloc** (1024 * *f*);
    if (*c* is equal to NULL) **then break;**
    for each position in c
        c[position] = 0;
    sleeps for *t* seconds;
    free (*c*);
end loop

Algorithm 2. Memory leaking

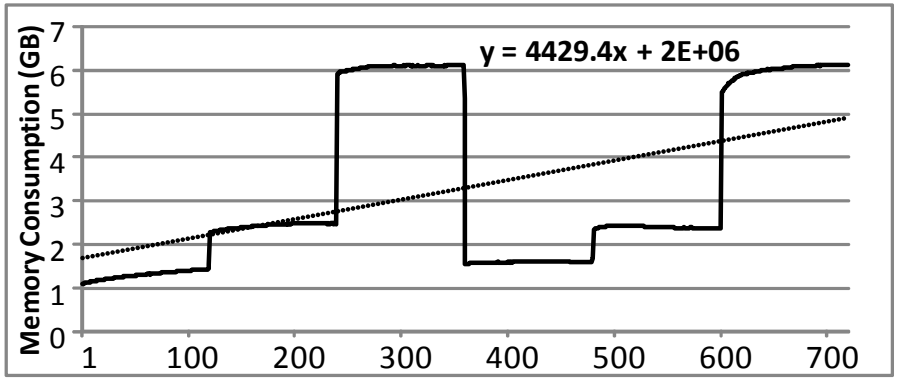
t: sleep time in seconds
f: multiple of page size
k: luck number
loop
    t = **random** (1..30);
    f = **random** (1..5);
    c = **malloc** (1024 * *f*);
    if (*c* is equal to NULL) **then break;**
    for each position in c
        c[position] = 0;
    sleeps for *t* seconds;
    k = **random** (even..odd);
    if (*k* is even) **then free** (*c*);
end loop

Experiment #2

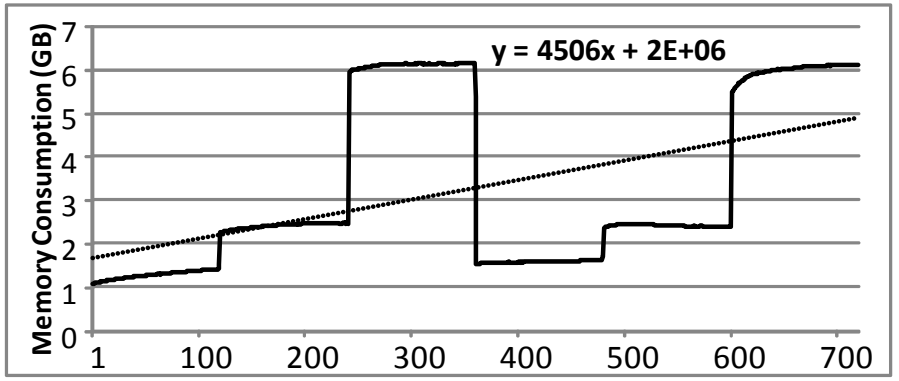
Table 2. Test Profiles for Experiment #2

Test	Profile
2.1	No memory leaking (baseline)
2.2	Memory leak inside the App.
2.3	Memory leak inside the OS kernel
2.4	Memory leak inside the App. & OS kernel

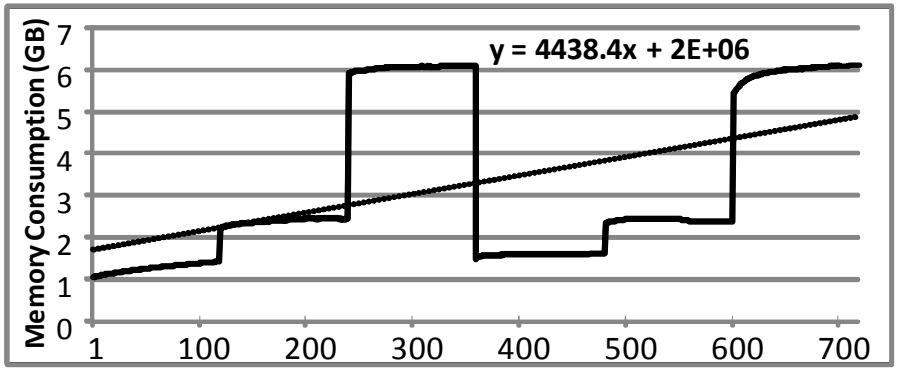
Experiment #2



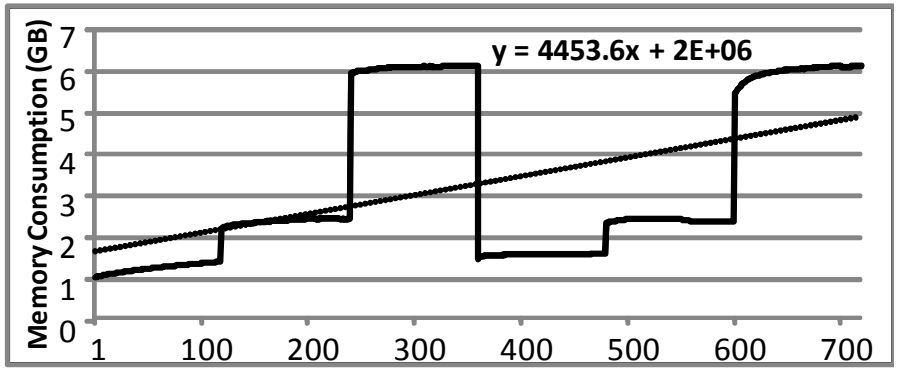
(a)



(b)



(c)



(d)

Experiment #2

- As can been seen, all tests of Exp. #2 show similar results.
- The background workload forces the OS disk caching effect
  - that dominates the memory usage variability in the system, thus hiding most of the aging effects injected.
- In average, the predominant size of memory allocations is less than 64 bytes, which is easily obfuscated by the larger variability of many usual background workloads
  - e.g., in Exp. #2 the average amount of memory leaked was 200 kilobytes within six hours.

Conclusion #2

- We can conclude that system-wide aging indicators suffer different influences (e.g., background tasks), making their quality poor.
- If you need to use them, we recommend adopting a baseline in order to reduce (not avoid) the risks of false positives.
- Application-specific aging indicators are a better alternative to offer noise-free information.

Using Application-specific indicators

- Specially for detecting memory leaks, we proposed [Matias et al. 2006] the use of the process' resident set size (RSS) as aging indicator.
- This indicator allows us to monitor the specific amount of main memory that a given application process is using.
- Monitoring this indicator is more effective than using system-wide indicators such as free or used main memory.

Using Application-specific indicators

- However, in recent findings we learned that memory leaks do not increase the process resident size (RSS) immediately to their occurrences.
  - because the process size is only increased when a new memory area is requested to the OS in order to enlarge the saturated heap.
  - it could take some time to observe leaking effects only monitoring the RSS
- As a result, now we know that the RSS may present some detection delay.
  - this delay depends on the memory allocator algorithm used.

Experiment #3

- In this experiment, we execute a program that initially allocates 1024 blocks of 1024 bytes (1 megabyte in total).
- Then we free the first 512 blocks and allocate new 512 blocks, but now leaking all of them.

Experiment #3

```
char *p[1024];
main(){
  unsigned long j=0,i=0,l=0;

  for(i=0; i<1024;i++){
     p[i]=malloc(1024);
     if ( p[i]==NULL)  exit(0);
     for(l=0;l<1024;l++) p[i][l]='*';
   }

   for(i=0;i<512;i++)  free(p[i]);

   for(i=0; i<512;i++){
     p[0]=malloc(1024);
     if ( p[0]==NULL) exit(0);
     for(l=0;l<1024;l++) p[0][l]='*';
   }

}
```

Allocate 1 megabyte

Release 512 kilobytes

Allocate 512 kilobytes, leaking them

Experiment #3

```
char *p[1024];
main(){
  unsigned long j=0,i=0,l=0;
                                        RSS= 224 kB
  for(i=0; i<1024;i++){
     p[i]=malloc(1024);
     if ( p[i]==NULL)  exit(0);
     for(l=0;l<1024;l++) p[i][l]='*';
   }

   for(i=0;i<512;i++)  free(p[i]);

   for(i=0; i<512;i++){
     p[0]=malloc(1024);
     if ( p[0]==NULL) exit(0);
     for(l=0;l<1024;l++) p[0][l]='*';
   }

}
```

Experiment #3

```
char *p[1024];
main(){
  unsigned long j=0,i=0,l=0;
                                        RSS= 224 kB
  for(i=0; i<1024;i++){
     p[i]=malloc(1024);
     if ( p[i]==NULL)  exit(0);
     for(l=0;l<1024;l++) p[i][l]='*';
   }
                                        RSS= 1276 kB
   for(i=0;i<512;i++)  free(p[i]);

   for(i=0; i<512;i++){
     p[0]=malloc(1024);
     if ( p[0]==NULL) exit(0);
     for(l=0;l<1024;l++) p[0][l]='*';
   }

}
```

Experiment #3

```
char *p[1024];
main(){
  unsigned long j=0,i=0,l=0;
```

RSS= 224 kB

```
  for(i=0; i<1024;i++){
     p[i]=malloc(1024);
     if ( p[i]==NULL)  exit(0);
     for(l=0;l<1024;l++) p[i][l]='*';
   }
```

RSS= 1276 kB

```
   for(i=0;i<512;i++)  free(p[i]);
```

RSS= 1276 kB

```
   for(i=0; i<512;i++){
      p[0]=malloc(1024);
      if ( p[0]==NULL) exit(0);
      for(l=0;l<1024;l++) p[0][l]='*';
   }

}
```

Experiment #3

```
char *p[1024];
main(){
  unsigned long j=0,i=0,l=0;
```

RSS= 224 kB

```
  for(i=0; i<1024;i++){
     p[i]=malloc(1024);
     if ( p[i]==NULL)  exit(0);
     for(l=0;l<1024;l++) p[i][l]='*';
   }
```

RSS= 1276 kB

```
   for(i=0;i<512;i++)  free(p[i]);
```

RSS= 1276 kB

```
   for(i=0; i<512;i++){
      p[0]=malloc(1024);
      if ( p[0]==NULL) exit(0);
      for(l=0;l<1024;l++) p[0][l]='*';
   }
```

RSS= 1276 kB

```
}
```

Experiment #3

- The common sense would expect that right after releasing the memory, it would be returned to the OS (reflecting on the RSS).
- The observed behavior is specific for the memory allocator used, *ptmallocv2*, which moves the released blocks to its heap's free lists in order to keep them for a possible future use.
- Note that replacing the allocator the results will be different.
- In addition to the RSS detection delay, now we know that not all leaking scenarios are captured monitoring only the RSS.

Conclusions

- Our experiments indicate that a precise memory leak monitoring should be done inside the process' heap rather than outside, as it has been implemented so far.
- Monitoring the RSS is better than other system-wide aging indicators, but also presents drawbacks.
  - it could not reveal precisely the correct memory leak rate, due to detection delays and the influences of the allocator design.
- Hence, only analyzing the RSS is also not sufficient to conclude about the existence of memory leaks.

Suggestions

- To verify if the increasing of RSS should be considered or not a consequence of memory leaks, we propose:
  - testing the application in a controlled environment, where it is possible to reduce the amount of physical memory.
  - If the process size still growing behind the limits of the physical memory, i.e., increasing its virtual memory size (VSZ), then it must be considered a memory leak problem.
  - If not, then the VSZ should not be significantly larger than the RSS, which is limited to the available physical memory.
  - Therefore, we consider that monitoring the RSS in conjunction with the process virtual size (VSZ) is a better strategy than using only the RSS.

Thank You!

Rivalino Matias Jr.

rivalino@fc.ufu.br