

Page frame reclaiming algorithms

Johan Montelius and Amir H. Payberah

Introduction

In this assignment, you will explore some of the page frame reclaiming algorithms.

1 Pick one by random

To set a standard and see if we actually do something useful, we first implement the algorithm where we select a frame randomly. If we later experiment with very complicated algorithms, we hope they behave better than random; otherwise, why would we bother to implement something complex? Create a file `random.c` and open up your favorite editor. Do not use an IDE that hides all the complicated things; use a regular text editor and do the compilation by hand from a command shell.

1.1 A random sequence

The first thing we shall do is to generate a random sequence of page identifiers. This sequence is the page reference sequence that we will use in our benchmark of the algorithm. We could have generated these references on the fly, but we need them when we implement the optimal strategy, so we might as well do it now. Below, first, you go at the `random.c` program. It will only write out a sequence of random numbers, but it is only a start. Compile the code and do a test run to see that it works.

```

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <assert.h>

void init(int *sequence, int refs, int pages) {
    for (int i = 0; i<refs; i++)
        sequence[i] = rand() % pages;
}

int main(int argc, char *argv[]) {
    /* could be command line arguments */
    int refs = 10;
    int pages = 100;

    int *sequence = (int*)malloc(refs * sizeof(int));
    init(sequence, refs, pages);

    /* a small experiment to show that it works */
    for(int i = 1; i < refs; i++)
        printf(", %d", sequence[i]);

    printf("\n");
    return 0;
}

```

So we have a random sequence of references, but we need to make things a bit more interesting. The more advanced algorithms are based on the fact that page references will probably not be completely randomized. They make use of the fact that some pages are referenced more often than others. To make the sequence look more like a real-life sequence, we change the initialization to produce a sequence where 20% of the pages are referenced 80% of the time (spatial locality).

```

/* 20% of the pages will have 80% of the references */
#define HIGH 20
#define FREQ 80

void init(int *sequence, int refs, int pages) {
    int high = (int)(pages*((float)HIGH/100));

    for (int i = 0; i<refs; i++) {
        if(rand() % 100 < FREQ) /* the frequently case */
            sequence[i] = rand() % high;
        else /* the less frequently case */
            sequence[i] = high + rand() % (pages - high);
    }
}

```

Note that this is a crude way of approximating a sequence of page references. There is, for example, no *temporal locality* that would make it more likely that we reference pages that we have recently referenced. To capture this, we would have to include a memory in the generator so that it had a preference for, say, the last ten pages rather than jumping to a random

page. The model we have will do for our simple experiment, but to do a better evaluation, one would need a better approximation and actual data from real executions.

1.2 Keep track of the pages

In our experiments, we will not swap pages in or out but simply keep track of how many times we would have to do it if we used the algorithms in a real system. We can therefore keep things quite simple and only track if a page is allocated or not. We will keep a *page table* with one entry per page, and each entry, a *page table entry*, will tell us if a page is in memory or not (the *presence bit*).

```
typedef struct pte {
    int present;
} pte;
```

In the main procedure, we allocate memory for the page table. If we know that we always will use a page table of size 100, we can allocate it on the stack using the following construct (with `PAGES` defined as a macro).

```
pte table[PAGES];
```

If we rather have the number of pages being given at run-time, we need to allocate the structure on the *heap* using a call to `malloc()`.

```
pte *table = (pte *)malloc(pages*sizeof(pte));
```

1.3 The simulation

Now we are ready to do the simulation and will simulate what would happen in a system with a given set of frames. As the number of frames increases, we will have room for more of the pages, and when we have as many frames as we have pages, there will be no swapping at all. This is the structure of the benchmark. We compute an increment, the number of pages divided by the number of data points, and then run the simulation for a growing number of frames. Keep the output as shown. We will later process the data and produce a nice graph. The procedure `clear_page_table(int *page_table, int pages)` should run through the page table and set the present bits to zero. Complete the code with `SAMPLES` as a defined macro set to 20.

```

printf("# This is a benchmark of random replacement\n");
printf("# %d page references\n", refs);
printf("# %d pages \n", pages);
printf("#\n#\n#frames\tratio\n");

/* frames is the size of the memory in frames */
int frames;
int incr = pages / SAMPLES;

for(frames = incr; frames <= pages; frames += incr) {
    /* clear page tables entries */
    clear_page_table(table, pages);
    int hits = simulate(sequence, table, refs, frames, pages);
    float ratio = (float)hits / refs;
    printf("%d\t%.2f\n", frames, ratio);
}

```

The `clear_page_table()` is easily defined as below.

```

void clear_page_table(pte *page_table, int pages) {
    for(int i=0; i < pages; i++)
        page_table[i].present = 0;
}

```

In the heart of the simulator, we read the references one by one to determine if it would have given us a hit in the memory or a page fault. If we have a hit, we are happy, but if not, we must do some more work. If we still have free frames, we simply mark the page as being in memory, but if the number of allocated pages is equal to the available number of frames, we need to evict a page.

```

int simulate(int *seq, pte *table, int refs, int frms, int pgs) {
    int hits = 0;
    int allocated = 0;

    for(int i = 0; i < refs; i++) {
        int next = seq[i];
        pte *entry = &table[next];

        if (entry->present == 1) {
            hits++;
        } else {
            if (allocated < frms) {
                allocated++;
                entry->present = 1;
            } else {
                pte *evict;
                do {
                    int rnd = rand() % pgs;
                    evict = &table[rnd];
                } while(evict->present != 1);

                evict->present = 0;
                entry->present = 1;
            }
        }
    }

    return hits;
}

```

In this simulation, we will select a page at random. We will not be very efficient in this process (why?), but it is fine for our purposes. We simply generate a random page number and check if it is in memory. When we find a page, we mark it as swapped and mark the new page as in memory.

1.4 Generating a graph

If you have the program up and running, you should be able to generate a sequence of data points. This is all fine, but we would like to generate a nice graph on the fly.

```

# This is a benchmark of random replacement policy
# 100000 page references
# 100 pages
#
# frames  ratio
5  0.13
10 0.28
15 0.41
:

```

The first thing we do is to write the output to a file. We could have written our program in a way that opens and writes the data to the file, but a simpler way is to use the shell to do it for us. Try the following in your

shell.

```
$ gcc random.c -o random
$ ./random > random.dat
$ more random.dat
```

So now we have a file called `random.dat` with the data we want to plot. Now in a shell, run the program `gnuplot`. If it is not installed, it should be a two min job to install it. If `gnuplot` starts, try the following.

```
gnuplot> plot "random.dat" u 1:2
```

If everything works, you should see a window with a nice graph of the data points. You have just told `gnuplot` to plot the data in the file `random.dat` using columns 1 and 2. `Gnuplot` will ignore all lines starting with a `#`, so this is why we generated the output as we did. You can explore `gnuplot` using the command line, but after a while, you want to write a script that generates the plot you want. Save the following in a file called `random.p`.

```
# Gnuplot script for plotting data in file "random.dat"
set terminal png
set output "random.png"
set title "Page replacement using random policy"
set key right center
set xlabel "frms in memory"
set ylabel "hit ratio"
set xrange [0:100]
set yrange [0:1]

plot "random.dat" u 1:2 w linespoints title "random"
```

You can now generate the file `random.png` by giving the script file to `gnuplot` as a command line argument.

```
$ gnuplot random.p
```

`Gnuplot` is an excellent tool when you want to generate nice graphs from data in text files. It is not a program to do statistical calculations of the data, so it requires that you can generate the data that you want to turn into a graph.

Figure 1 includes the graph in this document that is prepared using `gnuplot` inside `LATEX`. If you have not learned how to use `LATEX` it is high time to do so. It is a bit of a learning curve but well worth it once you start working on your thesis.

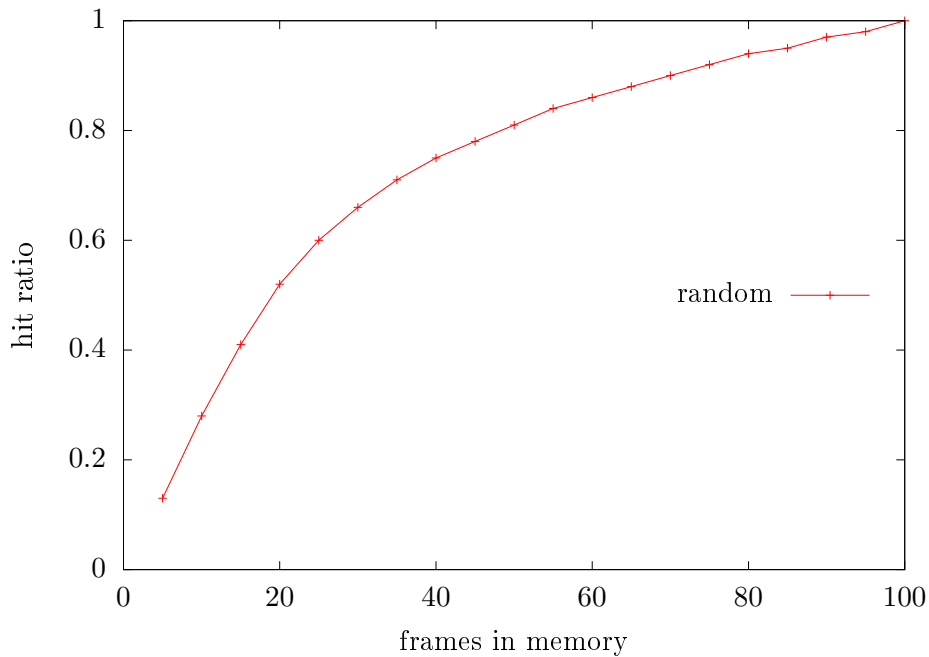


Figure 1: The random data in a nice graph.

2 The optimal solution

To estimate how well our random solution works, we implement an optimal solution, even though we know that the optimal solution is not something that we will be able to use in practice. The optimal solution will throw out the page that will not be used for the longest period. We can determine this since we have the complete sequence of requests (something that we would not have in a real situation).

The optimal solution is quite easy to implement, but our implementation will not be particularly efficient. When it is time to evict a page, we will simply go through all pages in memory and check how far down the sequence of references it is found. The page with the highest value is selected.

```

pte *evict;

/* initial values */
int sofar = 0;
int candidate = pgs;

for (int c = 0; c < pgs; c++) {
    if (table[c].present == 1) {
        /* the page is allocated */
        int dist = 0;
        while(seq[i + dist] != c && i + dist < refs)
            dist++;

        if (dist > sofar) {
            candidate = c;
            sofar = dist;
        }
    }
}

evict = &table[candidate];
evict->present = 0;
entry->present = 1;

```

Make a copy of `random.c` called `optimal.c` and do the following changes to the `simulation()` procedure. Finding a more efficient algorithm to implement the optimal solution is quite a fun challenge. It is obvious that it is a waste of time to calculate the distance of all pages every time we have a page fault. We should be able to keep a list of all the pages in memory, ordered by the next position in the sequence. It is a bit tricky to figure out how to do it, but the solution is quite simple once you get it right. The reward is not so much that we will cut the time for our benchmark in half but the satisfaction of figuring out how to do it.

2.1 How to proceed

If we look at the data, we see that there is certainly room for improvement. Even if the optimal policy does not give us a system without page faults, the reduced number of faults will dramatically increase performance. If we can implement something that is only halfway towards the optimal policy, much would be gained.

3 Least Recently Used

We will first implement something that works quite well, the *least recently used policy*. The only problem with this policy is that it is quite costly, and it is important to understand why this is.

3.1 A list of the last referenced pages

Let's keep a list of the last referenced pages, the ones that are in memory. We will keep the list ordered and have the least recently used page first in the list and the most recently referenced page last. When we reference a page that is in memory, the page is also in the list. We then move the page to the end of the list to keep the list ordered. If the memory is full, we evict the page that is the first page in the list since this page is the least recently used.

We could create a new data structure to keep track of the list, but we will keep things simple and extend the page table entry to keep a *next* and *previous pointer*. These pointers are used if the page is present in memory and thus linked in the list.

```
typedef struct pte {
    int id;
    int present;
    struct pte *next;
    struct pte *prev;
} pte;
```

In the simulation, we keep track of the *first* and *last* elements of the list. Keeping track of the last element will allow us to quickly add a new entry to the end of the list. Keeping the list double-linked allows us quickly unlink an entry. We can change the `simulate()` procedure, and the structure would look as follows.

```

int simulate(int *seq, pte *table, int refs, int frames, int pgs) {
    int hits = 0;
    int allocated = 0;

    pte *first = NULL;
    pte *last = NULL;

    for (int i = 0; i < refs; i++) {
        int next = seq[i];
        pte *entry = &table[next];

        if (entry->present == 1) {
            hits++;
            :
            /* unlink entry and place last */
            :
        } else {
            if (allocated < frames) {
                allocated++;
                entry->present = 1;
                entry->prev = last;
                entry->next = NULL;
                :
                /* place entry last */
                :
            } else {
                pte *evict;
                evict = first;
                first = evict->next;
                evict->present = 0;
                entry->present = 1;
                entry->prev = last;
                entry->next = NULL;
                :
                /* place entry last */
                :
            }
        }
    }

    return hits;
}

```

The errors you will encounter when you implement the procedure are the corner cases. It is straightforward to unlink an entry if it is in the middle of a list. But what happens if it is the first item in the list? What if it is the only entry in the list? You will get it right but do use a pen and paper and make some drawings of how the pointers have changed.

3.2 Much better, but costly

If you get the data from the LRU implementation, you should see that it is better than the random selection. It could be even better if the sequence of references showed more temporal locality. The problem with the LRU algorithm is that it will cost you even if you do not have a page fault. If you look at the implementation of the random algorithm, you will see that hardly

anything is done when we have a page hit. We increment a counter, but this is only for our purposes of collecting some statistics. Compare this with the LRU implementation, where a double-linked list must be manipulated.

We can not expect to reduce the number of page faults much more than what we have with the LRU algorithm (apart from having good luck), but we hope to stay close to LRU as possible even if we reduce the amount of work done when we have page hits.

4 The clock algorithm

The clock algorithm is a clever algorithm that could be explained in terms of a list similar to the one used in the LRU algorithm. The difference is that the list is not updated with each reference. It becomes a simple FIFO queue of entries which does not help us very much. The trick is that we keep an extra flag in the page table entry that keeps track of if the page has been referenced since it was last cleared. If the page we are about to evict has the reference flag set, it is placed last in the list, so it is given a *second chance*.

If we frequently move entries from the beginning to the end of the list, we might as well let the entries form a ring where we keep track of where the list starts. This is why it is called the clock algorithm.

4.1 A single linked list

It turns out that we will be fine with a single linked circular list. We will not unlink a random entry but only the first entry in the ring, and this is much easier if the list is only single-linked.

```
typedef struct pte {
    int id;
    int present;
    int referenced;
    struct pte *next;
} pte;
```

Our *clock handle* will point to the last entry in the circular list so the entry which is a candidate for eviction will be one entry ahead. The simulator now has the following structure.

```

int simulate(int *seq, pte *table, int refs, int frms, int pgs) {
    int hits = 0;
    int allocated = 0;
    pte *last = NULL;

    for (int i = 0; i < refs; i++) {
        int next = seq[i];
        pte *entry = &table[next];

        if (entry->present == 1) {
            entry->referenced = 1;
            hits++;
        } else {
            if (allocated < frms) {
                allocated++;
                entry->present = 1;
                :
                /* place the entry last in the list */
                :
            } else {
                pte *cand = last->next;

                while (cand->referenced != 0 ) {
                    cand->referenced = 0;
                    last = cand;
                    cand = cand->next;
                }

                cand->present = 0;
                cand->referenced = 0;
                entry->present = 1;
                entry->referenced = 0;
                :
                /* place the entry last in the list */
                :
            }
        }
    }
}

return hits;
}

```

As you see, there is only one tricky case - where we are still building the ring. We have to cover the corner case where there are no entries in the ring, and we are adding the first one. Apart from this, the implementation is quite simple. If you look at the figures generated, you will see that it sometimes even outperforms LRU (but this is more based on luck). Take a look at the code - what do we need to do when we have a page hit? As you see, we are in pair with LRU but with a very limited amount of extra work. If the updating of the page table can be done in hardware, the overhead is negligible.

4.2 Problems and extensions

Although the clock algorithms work fine in our benchmark, the reality is often more complicated. What will happen if all of the pages are referenced?

We will traverse the ring and reset the reference flags and then evict a page that was actually referenced since the last page fault. If we had a counter, we could at least choose a page that had been referenced the least number of times. A time stamp would be able to give us information on when the page was last used etc.

Using only one bit to keep track of frequently and recently used pages is an approximation. There are more advanced implementations, but the problem is that we must keep the overhead for page hits to a minimum. You can take some penalty when we have a page fault, but we do not want to examine all frames in memory to decide which one to evict.

Whatever we do, we must remember that real life is more complicated than benchmarks. If we lure ourselves into thinking that the benchmark sequence is what real-life sequences look like, then we might optimize our system for the benchmarks rather than reality. To improve the implementation, it might be more important to make the frequent case as fast as possible rather than trying to avoid a page fault at all costs.