COMP 40 Assignment: Locality and the costs of loads and stores

Overview and purpose

This assignment is all about the cache and locality. You'll implement **blocked** two-dimensional arrays, which you'll then use to evaluate the performance of image rotation using three different array-access patterns with different locality properties. You'll also see how to write code that is polymorphic in an array type.

The assignment has two parallel tracks:

1. On the *design and building track*, you will implement *blocked* two-dimensional arrays and *polymorphic* image rotation,

2. On the *experimental computer-science track*, you will predict the costs of image rotations, and later measure them. Your predictions will be based on knowledge of the cache as covered in Chapter 6 of Bryant and O'Halloran and as covered in class.

As described in Section 2, in this assignment we provide you with a *lot* of code and information. It will take time to assimilate. You can get some of the code by running the commands

```
git clone /comp/40/git/locality
cd locality
```

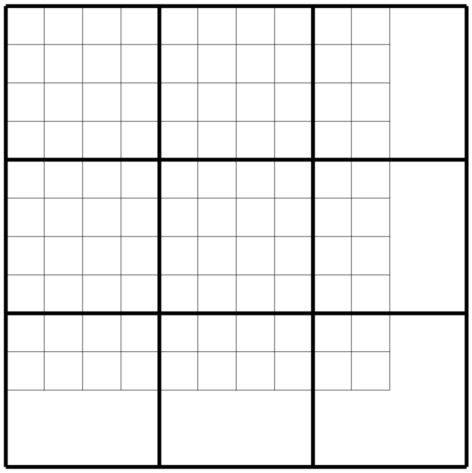
which will create and enter a directory called `locality`. Do this at the start of the assignment.

Contents

1 Problems

1.1 Part A (design/build): Improving locality through blocking

In this part of the assignment, you will implement a standard technique for improving locality: *blocking*. The idea is best expressed in a picture. Here is a 10-by-10 array organized in 4-by-4 blocks:



The idea is simple: the blocked array has a similar *interface* to `UArray2`, but a different *cost model.* In particular,

- **Cells in the same block are located near each other in memory**.
- **Mapping is done by blocks**, not rows or columns. Mapping visits all cells in one block before moving on to the next block.
- **Some memory is wasted** at the right and bottom edges: not all the cells in those blocks are used. But if the array is large, then the wasted memory has size $O(\sqrt{n})$ and is unimportant. If the array is small, it probably fits in the cache and you shouldn't use blocking.

You have just one task for this part:

- **Implement blocked arrays** as described in the `UArray2b` interface below. Use file `uarray2b.c`.

Required interface

Since you have already been through a very similar design exercise, I will not ask you to repeat it. Instead, I am specifying an interface, and I suggest a design which you may use if you wish. The interface you are to implement, to be called `UArray2b`, appears in Figure 1. The `blocksize` parameter to `UArray2b_new` counts the number of *cells* on **one side** of a block, so the actual number of cells in a block is `blocksize * blocksize`. The number of *bytes* in a block is `blocksize * blocksize * size`. The `blocksize` parameter has no effect on semantics, only on performance.

The `UArray2b_new_64K_block` allows you to default the blocksize; it is similar to `UArray2_new`. It chooses a `blocksize` that is as large as possible while still allowing a block to fit in 64KB of RAM. If a single cell will not fit in 64KB, the block size should be 1. The reasonably fast L2 caches on most modern machines will hold between 128 KB and 256 KB of data, so if you create arrays using `UArray2b_new_64K_block`, you can fit two blocks in cache at one time.

```
#ifndef UARRAY2B_INCLUDED
#define UARRAY2B_INCLUDED

#define T UArray2b_T
typedef struct T *T;

/*
 * new blocked 2d array
 * blocksize = square root of # of cells in block.
 * blocksize < 1 is a checked runtime error
 */
extern T    UArray2b_new (int width, int height, int size, int blocksize);

/* new blocked 2d array: blocksize as large as possible provided
 * block occupies at most 64KB (if possible)
 */
extern T    UArray2b_new_64K_block(int width, int height, int size);

extern void  UArray2b_free     (T *array2b);

extern int   UArray2b_width    (T  array2b);
extern int   UArray2b_height   (T  array2b);
extern int   UArray2b_size     (T  array2b);
extern int   UArray2b_blocksize(T  array2b);

/* return a pointer to the cell in the given column and row.
 * index out of range is a checked run-time error
 */
extern void *UArray2b_at(T array2b, int column, int row);

/* visits every cell in one block before moving to another block */
extern void  UArray2b_map(T array2b,
                          void apply(int col, int row, T array2b,
                                     void *elem, void *cl),
                          void *cl);

/*
 * it is a checked run-time error to pass a NULL T
 * to any function in this interface
 */

#undef T
#endif
```

Figure 1: Interface for blocked arrays

One possible architecture for your implementation

If you wish, you may use your own design and architecture for the implementation of `UArray2b`, or you may use one of mine described as follows:

> Here is a simple architecture for `UArray2b`. Because of the many layers of abstraction, it does not perform very well, but it is relatively easy to implement.
>
> - An `UArray2b_T` can be represented as an `UArray2_T`, each element of which contains one block.
> - A block should be represented as a single `UArray_T`. This representation guarantees that cells in the same block are in nearby memory locations.
> - To find the cell at index (i, j), first find the block at index (`i / blocksize`, `j / blocksize`). Within that block, use the cell at index `blocksize * (i % blocksize) + j % blocksize`.
> - Your mapping function should visit all the cells of one block before moving onto the cells of the next. **Blocks on the bottom and right edges may have unused cells**, and your mapping function must **not** visit these cells.

If you implement this design successfully, it is not too difficult to modify the code such that your blocked array is stored in a single, contiguous area of memory. Once you have the address arithmetic right, you can get a substantial speedup by avoiding all the memory references involved in going indirectly through the `UArray2` and `Array` abstractions. But the focus of this assignment is not primarily on performance. We expect your program to run at reasonable speed, but you will do fine with the `UArray2b` design outlined above. If you prefer, you can try a different approach.

Our solutions

Norman Ramsey wrote two solutions to this problem. The one that uses the design sketched above is about 175 lines of C, 50 of which appear at the end of this assignment. He then wrote another, faster solution which is about 130 lines of C. The faster solution has a significantly more complicated invariant and was correspondingly more difficult to get right.

```
typedef void *A2;               /* unknown type that represents a
                                 * 2D array of 'cells'
                                 */

typedef void A2Methods_Object;  /* an unknown sequence of bytes in memory
                                 * (element of an array)
                                 */

typedef void A2Methods_applyfun(int i, int j, A2 array2,
                                A2Methods_Object *ptr, void *cl);
typedef void A2Methods_mapfun(A2 array2, A2Methods_applyfun apply, void *cl);

typedef void A2Methods_smallapplyfun(A2Methods_Object *ptr, void *cl);
typedef void A2Methods_smallmapfun(A2 a2, A2Methods_smallapplyfun f, void *cl);


/*              CONTINUED ON NEXT PAGE                         */
```

Figure 2: Polymorphic interface for manipulating two-dimensional arrays - Part 1 of 2

```
typedef struct A2Methods_T {
        /* creates a distinct 2D array of memory cells, each of the given 'size'
         * each cell is uninitialized
         * if the array is blocked, uses a default block size
         */
        A2(*new) (int width, int height, int size);

        /* creates a distinct 2D array of memory cells, each of the given 'size'
         * each cell is uninitialized
         * if the array is blocked, the block size given is the number of cells
         *    along one side of a block; otherwise 'blocksize' is ignored
         */
        A2(*new_with_blocksize) (int width, int height, int size,
                                 int blocksize);

        /* frees *array2p and overwrites the pointer with NULL */
        void (*free) (A2 * array2p);


        /* observe properties of the array */
        int (*width)     (A2 array2);
        int (*height)    (A2 array2);
        int (*size)      (A2 array2);
        int (*blocksize) (A2 array2);   /* for an unblocked array, returns 1 */

        /* returns a pointer to the object in column i, row j
         * (checked runtime error if i or j is out of bounds)
         */
        A2Methods_Object *(*at) (A2 array2, int i, int j);

        /* mapping functions */
        /* each mapping function visits every cell in array2, and for each
         * cell it calls 'apply' with these arguments:
         *    i, the column index of the cell
         *    j, the row index of the cell
         *    array2, the array passed to the mapping function
         *    cell, a pointer to the cell
         *    cl, the closure pointer passed to the mapping function
         *
         * These functions differ only in the *order* in which they visit cells:
         *   - row_major visits each row before the next, in order of increasing
         *     row index; within a row, column numbers increase
         *   - col_major visits each column before the next, in order of
         *     increasing column index; within a column, row numbers increase
         *   - block_major visits each block before the next; order of
         *     blocks and order of cells within a block is not specified
         *   - map_default uses a default order that has good locality
         *
         * In any record, map_block_major may be NULL provided that
         * map_row_major and map_col_major are not NULL, and vice versa.
         */
        void (*map_row_major)  (A2 array2, A2Methods_applyfun apply, void *cl);
        void (*map_col_major)  (A2 array2, A2Methods_applyfun apply, void *cl);
        void (*map_block_major)(A2 array2, A2Methods_applyfun apply, void *cl);
        void (*map_default)    (A2 array2, A2Methods_applyfun apply, void *cl);

        /*
         * alternative mapping functions that pass only
         * cell pointer and closure
         */
        void (*small_map_row_major)  (A2 a2, A2Methods_smallapplyfun apply,
                                      void *cl);
        void (*small_map_col_major)  (A2 a2, A2Methods_smallapplyfun apply,
                                      void *cl);
        void (*small_map_block_major)(A2 a2, A2Methods_smallapplyfun apply,
                                      void *cl);
        void (*small_map_default)    (A2 a2, A2Methods_smallapplyfun apply,
                                      void *cl);

} *A2Methods_T;
```

Figure 3: Polymorphic interface for manipulating two-dimensional arrays - Part 2 of 2

1.2 Part B (design/build): supporting polymorphic manipulation of 2D arrays

You now have two different representations of two-dimensional arrays: UArray2, which supports column-major and row-major mapping, and UArray2b, which supports block-major mapping. In order not to duplicate code, we want to write image rotations that can operate on *either* kind of array. To achieve this kind of reuse, we resort again to polymorphism: we define an interface A2Methods that can represent either kind of two-dimensional array. You write *one* image-rotation program against this interface, and you can use it with *two* implementations.

- Because I have specified the exact interface for UArray2b, I can provide an implementation of A2Methods that uses UArray2b.
- Because you designed the UArray2 interface yourself, *you* will provide an implementation of A2Methods that uses UArray2. My implementation is in file a2blocked.c; **your implementation goes into** a2plain.c.

The A2Methods interface uses the same principles as the declaration of an abstract class in a language like C++, C#, Java, or Smalltalk. Instead of calling functions by name, you will call through *pointers* to functions. Those pointers live in a *method suite* of type A2Methods_T, which is a pointer to a record of function pointers (Figure 2). For each of these function pointers, you will need to create a static function that calls into UArray2. To implement your method suite, you put pointers to those functions into a struct. Looking at a2blocked.c will show you a complete example, and in Figure 4 we also provide a template for your a2plain.c.

The interface you are to implement is defined in a2plain.h:

```
#include <a2methods.h>

extern A2Methods_T uarray2_methods_plain; /* functions for normal arrays */
```

You should **write file a2plain.c, which implements this interface**. It should look something like the template in Figure 4. The only tricky bit is resolving differences in your apply functions. Let's suppose that your UArray2 apply and row-major map functions look like this:

```
typedef void UArray2_apply(int row, int col, void *elem, void *cl);
extern void UArray2_map_row_major(UArray2_T a2, UArray2_apply apply, void *cl);
```

This "inner" apply function is compatible with UArray2, but it might not be the same as the "outer" apply function used in the A2Methods interface shown in Figure 2. (Whether it is or isn't sufficiently compatible you will have to determine. Even if it is, then when you implement the "small" functions below it surely won't be.) The exported mapping function will receive an "outer" apply function that is surely compatible with the A2Methods interface, and if the two are not compatible already you will have to create an "inner" apply function that is compatible with your own personal UArray2 interface.

1. To do this, you will likely need to define a new closure type a2fun_closure, which holds the outer apply function and its closure, plus any other information that's expected by the outer apply function but not provided by the inner apply function. In this case, the "other information" is the array.
2. Define a new, "inner" apply function that can be passed to your UArray2_map_row_major. This apply function grabs information from the a2fun_closure, and it applies the "outer" apply function. In other words, it's just a proxy.
3. Your A2Methods version of map_row__major, which you'll export a pointer to, builds an a2fun_closure, and then calls UArray2_map_row_major using the new closure and the inner apply function. The new closure always contains the old closure and the outer apply function.

You can see a full example in Figure 5.

Here is a summary of your obligations for this part:

```c
#include <stdlib.h>

#include <a2plain.h>
#include "uarray2.h"

/*********************************************/
/* Define a private version of each function */
/* in A2Methods_T that we implement          */
/*********************************************/

static A2Methods_UArray2 new(int width, int height, int size)
{
        return UArray2_new(...);
}

static A2Methods_UArray2 new_with_blocksize(int width, int height,
                                            int size,  int blocksize)
{
        (void) blocksize;
        return UArray2_new(...);
}

/* ... many more private (static) definitions follow ... */

/*
 * now create the private struct containing pointers to the functions
 */

static struct A2Methods_T uarray2_methods_plain_struct = {
        new,
        new_with_blocksize,
        /* ... other functions follow in order,
                with NULL for those not implemented ...
        */
};

/*
 * finally the payoff: here is the exported pointer to the struct
 */

A2Methods_T uarray2_methods_plain = &uarray2_methods_plain_struct;
```

Figure 4: Boilerplate for implementing a struct pointer of type A2Methods_T

```c
typedef void UArray2_apply(int row, int col, void *elem, void *cl);
extern void UArray2_map_row_major(UArray2_T a2, UArray2_apply apply, void *cl);

struct a2fun_closure {
        A2Methods_applyfun *apply;   /* apply function as known to A2Methods */
        void               *cl;      /* closure to go with apply function    */
        A2Methods_UArray2   array2;  /* array being mapped over              */
};

static void apply_a2methods_using_array2_prototype(int row, int col,
                                                   void *elem, void *cl)
{
        struct a2fun_closure *f = cl;  /* function/closure originally passed */
        f->apply(col, row, f->array2, elem, f->cl);
}
```

```c
static void map_row_major(A2Methods_UArray2 array2, A2Methods_applyfun apply,
                          void *cl)
{
        struct a2fun_closure mycl = { apply, cl, array2 };
        UArray2_map_row_major(array2, apply_a2methods_using_array2_prototype,
```

- You submit a file `a2plain.c` which exports the single pointer `uarray2_methods_plain`.
- In the methods suite, you *must* implement all the methods from `new` through `at`.
- Of the mapping methods, you *must* implement `small_map_row_major`, `small_map_col_major`, and `small_map_default`. For `small_map_default`, you should use either a row-major or a column-major mapping, whichever you think has better locality.
- If you can, you *should* implement methods `map_row_major`, `map_col_major`, and `map_default`. For `map_default`, you should use either a row-major or a column-major mapping, whichever you think has better locality.
- Because `UArray2` does not support blocking, you *must not* implement `map_block_major` or `small_map_block_major`. These pointers must be `NULL`.

1.3 Part C (design/build): `ppmtrans`, a program with straightforward locality properties

Using the `A2Methods` abstraction, implement program `ppmtrans`, which is modelled on `jpegtran` and performs some simple image transformations. Program `ppmtrans` offers a subset of `jpegtran`'s functionality. The image-transformation options you may support are as follows:

```
-rotate 90
       Rotate image 90 degrees clockwise.

-rotate 180
       Rotate image 180 degrees.

-rotate 270
       Rotate image 270 degrees clockwise (or 90 ccw).

-rotate 0
       Leave the image unchanged.

-flip horizontal
       Mirror image horizontally (left-right).

-flip vertical
       Mirror image vertically (top-bottom).

-transpose
       Transpose image (across UL-to-LR axis).

-time <timing_file>
       Create timing data (see Section 1.5 below) and store
       the data in the file named <timing_file>.
```

You must implement 0-degree, 90-degree and 180-degree rotations and the `-time` option. Other options **may be implemented for extra credit**; if you choose not to implement them, reject the unimplemented options with a suitable error message written to `stderr` and a nonzero exit code. As usual, successful execution of an implemented option should result in an exit code of EXIT_SUCCESS, which is 0. If `ppmtrans` is run with no options, it defaults to a 0-degree rotation. If a filename is supplied and that filename cannot be opened for reading, the result must be an explanatory message on `stderr` and an exit with code EXIT_FAILURE. No output may be written to `stdout` or `stderr` except where instructions elsewhere in this specification specifically allow for or require it.

Significant requirements:

- Your program must also **recognize and implement these options**:

  ```
  -row-major
         Copy pixels from the source image using map_row_major
  -col-major
         Copy pixels from the source image using map_col_major
  -block-major
         Copy pixels from the source image using map_block_major
  ```

  If none of these options is provided, follow the example of the argument handling code below, which uses `methods->map_default`.

- You **must not call `UArray2` functions or `UArray2b` functions directly**. Instead you must call *indirectly* through the function pointers in a methods suite.

- You **must use the mapping functions defined in `a2methods.h` to perform the transform**, *not* nested `for` loops. (Reading the PPM file is always done in row-major order, because that's how the pixels are stored in the file.)

- For row-major and column-major mapping, you will use the methods suite `uarray2_methods_plain` that you will have created in Part B of this homework. For block-major mapping, you will use the methods suite `uarray2_methods_blocked` that we provide in interface `a2blocked.h`.

Your `ppmtrans` should read a single `ppm` image either from standard input or from a file named on the command line.

Your `ppmtrans` should write the transformed image to standard output. Note that your image will be written in the binary (not plain) `ppm` format, and that we give you code (described below) that will do this correctly. Specifically, you must use the services defined in `pnm.h` to read, write and free the image files. Also, you do not need to do any explicit error handling relating to incorrect image file formats: you may rely on the services defined in `pnm.h`, and you should not be catching the exceptions it raises. For help handling command-line options, see the suggested code at the end of this assignment.

Why this problem is interesting from a cache point of view:

> *If cells in a row are stored in adjacent memory locations, processing cells in a row has good spatial locality, but it's not clear about processing cells in a column. If cells in a column are stored in adjacent memory locations, processing cells in a column has good spatial locality, but it's not clear about processing cells in a row. In a 90-degree rotation, processing a row in the source image means processing a column in the destination image, and vice versa. Thus, the locality properties of 90-degree rotation are not immediately obvious.*
>
> *In a 180-degree rotation, rows map to rows and columns map to columns. Thus, whatever locality properties are enjoyed by the source-image processing are enjoyed equally by the destination-image processing. If you understand how your data structure works, then, you should find it easier to predict the locality of 180-degree rotation.*
>
> *In a blocked representation, the mapping of blocks to blocks is not obvious. To understand the locality properties of blocked array processing, you will have to think carefully.*

My solution to this problem is about 150 lines of code.

1.4 Part D (experimental): Analyze locality and predict performance

This part of the assignment is to be completed at the same time as your design work for parts A and C. Please **estimate the expected cache hit rate for reads** of each of the six operations in the table below. Assume that the images being rotated are **much too large to fit in the cache**.

	row-major access (UArray2)	column-major access(UArray2)	blocked access (UArray2b)
90-degree rotation			
180-degree rotation			

The first two columns should be your estimate of how your `UArray2` implementation would perform with row-major and column-major access respectively. The third column should be for block-major access, which obviously is for your `UArray2B` implementation.

Each estimate should be a **rank between 1 and 6**, with 1 being the best hit rate and 6 being the worst hit rate. If you think two operations will have about the same hit rate, give them the same rank. For example, if you think that both column-major rotations will have the most cache misses and will have about the same number of cache misses, rank them both 5 and rank the other entries 1 to 4. You can assume a cache size of approximately 128KB.

Justify your estimates on the grounds of **expected cache misses** and **locality**. *Your justifications will form a significant fraction of your grade for this part.*

Unfortunately, measuring hit rates is not so easy (although `valgrind` can do a lot). But what we are really interested in is the **effect of locality on performance**. We are therefore *also* asking you to **predict the relative performance** of each algorithm. But do make some simplifying assumptions:

- As before, assume that the images being rotated are **much too large to fit in the cache**.
- Assume that all function calls cost the same, and that each algorithm does the same number of function calls.
- Assume that the cost model for stores is approximately the same as the cost model for loads: if the store modifies a line already in the cache, the cost is about one cycle, but if the store writes an address that is *not* already in the cache, it costs about as much as a cache miss.[1]
- Assume that the **differences in performance are determined entirely by the amount of time spent in the mapping functions.**
- Depending on how you design your representation and your mapping algoriths, a mapping function may use one, two, three, or even four nested loops. Assume that **only the operations in the innermost loop** matter.

Under these assumptions, estimate the following quantities for each algorithm:

1. How many addition or subtraction operations are done for each pixel in the image?
2. How many multiplication operations are done for each pixel in the image?
3. How many division or modulus operations are done for each pixel in the image?
4. How many comparison operations (equality, less than, and so forth) are done for each pixel in the image, not forgetting any loop-termination conditions?
5. How many loads are done for each pixel in the image?
6. Of the loads in question 5, **what fraction hit in the cache**?

[1] This assumption oversimplifies the cache's behavior significantly, but it will be good enough to enable reasonable predictions of performance.

7. How many *stores* are done for each pixel in the image?
8. Of the stores in question 7, **what fraction are to lines that are already in the cache**?

If the answers to questions 1–5 and 7 are the same for two different algorithms, the relative performance will be determined only by the cache performance. If the answers to questions 1–5 and 7 are significantly different, you may find that a lot of arithmetic may cost more than a modest difference in the cache-miss rate. (As a rule of thumb, add and subtract cost the same as a load that hits in the cache, a multiply costs a bit more, and division/modulus cost even more. Comparisons vary, but in a well-behaved program a comparison typically costs about the same as an add or subtract.)

Please submit the *expected work per pixel* in a table like the following:

Kind of rotation	adds/subs	multiplies	divs/mods	compares	loads	hit rate	stores	hit rate
180-degree row-major								
180-degree column-major								
180-degree block-major								
90-degree row-major								
90-degree column-major								
90-degree block-major								

Once you have estimated the expected cost per pixel, please **estimate the expected speed** of each of the six operations in the table below. Your speed estimate should include the **cost of stores** as well as the cost of loads.

	row-major access	column-major access	blocked access
90-degree rotation			
180-degree rotation			

Your estimate should be a **rank between 1 and 6**, with 1 being the fastest and 6 being the slowest. If you think two operations will go at about the same speed, give them the same rank. For example, if you think that both column-major rotations will be the slowest and will run at about the same speed, rank them both 5 and rank the other entries 1 to 4.

To complete this problem successfully, you will need to understand the material presented in class and in Chapter 6 of Bryant and O'Hallaron.

1.5 Part E (experimental): Measure and explain improvements in locality

To help understand the performance of your program, you have implemented the optional `-time <filename>` command line argument. If this argument is given, then your program will produce timing data that can later be analyzed.

- **Carefully follow the instructions at `http://www.cs.tufts.edu/comp/40/homework/locality-timing` to learn about and integrate our timing library into your `ppmtrans.c`**
- You will find a very small supply of large images in `/comp/40/images/large`.
- You can create your own large image by using any JPEG file with `djpeg` and `pnmscale`. Experiment until you get something of reasonable size, I.e. one that takes enough CPU time to show interesting results, and is not too big to be practical. A few seconds of CPU time is ideal.

  Example command lines:

  ```
  djpeg /comp/40/images/from-wind-cave.jpg | pnmscale 3.5 |
     ./ppmtrans -rotate 90 | display -
  djpeg /comp/40/images/wind-cave.jpg | pnmscale 1.2 |
     ./ppmtrans -rotate 90 | display -
  ```

- If you need to store a large image, you can create files and directories in the `/data` area, and they will not count against your disk quota. Or you can request that your disk quota be enlarged to 2GB; fill out the form at

  `https://www.eecs.tufts.edu/userguide/forms/quota.php`

  and list me as faculty sponsor. Note that `/data` directories tend to be private per machine, so if you switch machines you might not find information you left in the `/data` directory of another.

- **Remember, the instructions at `http://www.cs.tufts.edu/comp/40/homework/locality-timing` have told you how to instrument `ppmtrans.c` so that it writes accurate timing information to a named timing file. IMPORTANT CHANGE: do not write performance data to `stderr` as the grading scripts check that `stderr` is empty for successful runs...write to a file (you can use `fopen` to create or append to the file, of course). Remember not to use `stdout` for your timing output, or it will interfere with your rotated image.**

Choose an image at a given scale and be sure to time *all* rotations on that image at the **same scale**. If you like, you can also do the same for other images of several different sizes: small ones may fit in caches and larger ones might not.

Note that our timing library records **CPU time**, which is the time the computer spends actually running your program. The time reported should, for the most part, be independent of whether anyone else is using the machine at the same time. Do make sure to do all your reported tests on the same machine, and indicate in your report which machine it is. Some computers are faster than others, of course, and those will report lower CPU times for a given input.

Always record not only the total time taken for each rotation, but also the time per input pixel. Since the number of total input pixels is `width * height` of your input image it should be trivial to have your `ppmtrans` output the number of pixels and time per pixel along with the total time. DO NOT SEPARATELY START AND STOP THE TIMER FOR EACH PIXEL! Just measure the time for the whole transformation, and then divide by total pixels to compute the average time per pixel.

2 Infrastructure that we provide

This section identifies infrastructure you can use for this assignment.

2.1 A polymorphic interface to two-dimensional arrays

1. Figure 2 on page 4 gives a polymorphic interface that describes a method suite for two-dimensional arrays. You will provide a method suite that works with your design and implementation of `UArray2`; we provide an implementation that works with `UArray2b`. For a rather simple example of how to use the 2D-array methods, see sample file `a2test.c` (item 5 below). The file `a2methods.h` appears in `/comp/40/include` and should not be copied.

2.2 Other interfaces we have designed for you

The interfaces below appear in `/comp/40/include`. **Do not copy these files**. You should be able to compile against any of these interfaces by using the option `-I/comp/40/include` with `gcc`.

2. Files `a2plain.h` and `a2blocked.h` define two interfaces that promise method suites. We implement `a2blocked.h`; you should be able to link against it by using the options `-L/comp/40/lib64 -l40locality` with `gcc`.

3. File `uarray2b.h` defines the `UArray2b` interface. (You write the implementation.)

4. File `pnm.h` defines functions you can use to read, write, and free portable pixmap (PPM) files (see `/comp/40/include/pnm.h` for the interface). It defines a representation for colored pixels. The pixmap itself is represented as type `void *`; you will use this code with the `A2Methods_T` methods.

   The `Pnm` interface uses the `A2Methods` interface.

   You should be able to link against our implementation of `pnm.h` by using the options

   ```
   -L/comp/40/lib64 -l40locality -lnetpbm
   ```

   with `gcc`.

2.3 Test code for two-dimensional arrays

5. As usual when implementing polymorphism in C, it is possible to make a mistake with `void *` pointers. You will therefore want to **run small test cases using `valgrind`** in order to flush out potential memory errors. We provide one sample test case in file `a2test.c`; it tests the `cell` and `at` methods as well as row-major mapping, if present. Before you can use it you will need to implement `uarray2b.c` or `a2plain.c` or both.

   Once you can build `a2test`, run `valgrind ./a2test`.

2.4 Other source code

6. We provide C source code for `a2blocked.c`, which you don't need to compile, but you might find useful to study. We also provide incomplete versions of `a2plain.c` and `ppmtrans.c`.

2.5 Where to get what

7. All of the C source we provide for you is in a git repository. That repository also contains a `Makefile` that builds `a2test`; you will need to extend the script to build `ppmtrans`.

   You get all these sources by

   ```
   git clone /comp/40/git/locality
   ```

   which will create a subdirectory `locality`. **We recommend you *begin* the assignment by creating a directory using `git clone`.**

8. Interfaces `uarray2b.h`, `a2methods.h`, `a2blocked.h`, and `a2plain.h` all appear in `/comp/40/include`. **Don't copy these interfaces**.

2.6 Geometric calculations we have done for you

What's important about this assignment is how locality stores affects performance, not how to rotate images. We therefore inform you that we believe

9. If you have an original image of size $w \times h$, then when the image is rotated 90 degrees, pixel (i, j) in the original becomes pixel $(h - j - 1, i)$ in the rotated image.

10. When the image is rotated 180 degrees, pixel (i, j) becomes pixel $(w - i - 1, h - j - 1)$.

3 What we expect from your preliminary submission

Your preliminary submission should include your **design work** for parts A and C as well as **all of part D**.

- For Part C, please use the design checklist for writing programs. We are especially interested in knowing **what additional components** you plan to use to implement `ppmtrans` and **how those components work together to solve the problem**. We expect you to describe a **modular architecture** and to exploit **procedural abstraction**.
- For Part A, please use the design checklist for abstract data types. If we ignore costs, then in the world of ideas, `UArray2b` **cannot be distinguished** from `UArray2`. So all of your test cases and examples carry over from the previous assignment. Repeat them with updates and improvements as necessary (incorporate any feedback you received from the previous assignment). We will have higher standards this time around.

  We expect you to pay special attention to the **representation** and its **invariants**. Please be sure your submission explains

  1. How you will translate cell coordinates (i, j) into a C pointer in *your* representation. (If you use my design, your explanation will probably involve block coordinates—or a block number—and the index of the cell within the block.) The best possible explanation is a *precise* one using a **set of equations**.
  2. How you will translate a location within *your* representation (which in my design would be the combination of block coordinates and the index of a cell within the block) back to pixel coordinates (i, j). The best possible explanation is a *precise* one using a **set of equations**.
  3. What representation you will use for a single block.
  4. What representation you will use for a 2-dimensional array of blocks.

Please submit two files:

- `DESIGN` or `design.pdf` for your design work for Parts A and C.
- `ESTIMATES` or `estimates.pdf` for your estimates of locality, work per pixel, and total cost

Submit using `submit40-locality-design`.

4 What we expect from your final submission

Your **implementation**, to be submitted using `submit40-locality`, should include

1. A `README` file which
   - Identifies you and your programming partner by name
   - Acknowledges help you may have received from or collaborative work you may have undertaken
   - Identifies what has been correctly implemented and what has not
   - Documents the architecture of your solutions.
   - **Give measured performance** for Part E and **explain** your results. Be sure to record in a table the following:
     - The sizes of the images used for each of your tests
     - The total CPU time and the time per input pixel for each rotation on each image you report. Making the simplifying assumption that our computers execute approximately 1,000,000,000 instructions per second, estimate for each rotation the number of instructions executed per input pixel rotated.

    - The name and model of the computer you ran your tests on as well as the CPU type and clock rate. (`more /proc/cpuinfo`)

  Below your table, discuss patterns you see in the results: for example, do certain rotations run faster when using blocked arrays vs. plain? If you try different sized images (not required but useful), is the number of instructions per pixel similar regardless of image size? If not, why not?

  - Says **approximately how many hours you have spent** completing the assignment

2. (Optional) If you happen to know how to use a spreadsheet or GNUPlot to create bar charts, you're welcome to include a few PDFs with charts of the interesting data from your tables. This is NOT required, but it might help you tell your story.

3. The file `ppmtrans.c`.

4. File `uarray2b.c`, which implements the `UArray2b` interface. This file should include internal documentation explaining your representation and its invariants.

5. File `a2plain.c`, which provides a method suite as described by the `a2methods.h` interface.

6. Any other files you may have created as useful components.

7. A `Makefile`, which, when run using

   ```
   make
   ```

   encounters no errors and builds *two* executable binaries: `a2test` and `ppmtrans`.

   - `ppmtrans` should be linked with `ppmtrans.o`, `uarray2.o`, `uarray2b.o`, `a2plain.o`, `a2blocked.o`, and probably with other relocatable object files and libraries.

5 Avoid common mistakes

Here are the mistakes most commonly made on this project:

- It's a mistake to submit, in place of an invariant, a narrative description of a sequence of events.
- It's a mistake to try to explain a complex invariant in informal English.
- It's a mistake to analyze a rotation experiment if the rotation completes in less than a few seconds.
- When two programs perform very differently, and the programs have very different loop structures, it's a mistake to try to explain performance differences by appealing to locality.

6 Code to handle command-line options and choose methods

To deal with command-line options in `ppmtrans.c`, consider the code below. This code does not help you decide if a file has been named on the command line, which determines whether you read from that file or from standard input. To make this decision, you will need to examine the values of `i` and `argc`.

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

#include "assert.h"
#include "a2methods.h"
#include "a2plain.h"
#include "a2blocked.h"
#include "pnm.h"

static void
usage(const char *progname)
{
        fprintf(stderr, "Usage: %s [-rotate <angle>] "
                "[-{row,col,block}-major] [filename]\n",
                progname);
        exit(1);
}

int main(int argc, char *argv[])
{
        char *time_file_name = NULL;
        int   rotation = 0;
        int   i;

        /* default to UArray2 methods */
        A2Methods_T methods = uarray2_methods_plain;
        assert(methods);

        /* default to best map */
        A2Methods_mapfun *map = methods->map_default;
        assert(map);

#define SET_METHODS(METHODS, MAP, WHAT) do {                            \
                methods = (METHODS);                                    \
                assert(methods != NULL);                                \
                map = methods->MAP;                                     \
                if (map == NULL) {                                      \
                        fprintf(stderr, "%s does not support "         \
                                        WHAT "mapping\n",               \
                                argv[0]);                               \
                        exit(1);                                        \
                }                                                       \
        } while (0)

        for (i = 1; i < argc; i++) {
                if (strcmp(argv[i], "-row-major") == 0) {
                        SET_METHODS(uarray2_methods_plain, map_row_major,
                                    "row-major");
                } else if (strcmp(argv[i], "-col-major") == 0) {
                        SET_METHODS(uarray2_methods_plain, map_col_major,
                                    "column-major");
                } else if (strcmp(argv[i], "-block-major") == 0) {
                        SET_METHODS(uarray2_methods_blocked, map_block_major,
                                    "block-major");
                } else if (strcmp(argv[i], "-rotate") == 0) {
                        if (!(i + 1 < argc)) {      /* no rotate value */
                                usage(argv[0]);
                        }
                        char *endptr;
                        rotation = strtol(argv[++i], &endptr, 10);
                        if (!(rotation == 0 || rotation == 90
                              || rotation == 180 || rotation == 270)) {
                                fprintf(stderr, "Rotation must be "
                                        "0, 90 180 or 270\n");
                                usage(argv[0]);
                        }
                        if (!(*endptr == '\0')) {    /* Not a number */
                                usage(argv[0]);
                        }
                } else if (strcmp(argv[i], "-time") == 0) {
                        time_file_name = argv[++i];
                } else if (*argv[i] == '-') {
                        fprintf(stderr, "%s: unknown option '%s'\n", argv[0],
                                argv[i]);
                } else if (argc - i > 1) {
                        fprintf(stderr, "Too many arguments\n");
                        usage(argv[0]);
                } else {
                        break;
                }
        }

         ...
}
```