Dynamic Memory and Cache

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Based on slides by Troels Henriksen

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Arrays

Locality of reference

Arrays

Definition

An array is a multidimensional sequence of objects of the *same type and size*.

- Arrays often used to represent mathematical objects such as *vectors*, *matrices*, and *tensors*.
- Probably the most common data structure for scientific data.
- The arrays we will cover in this lab (and course) are
  - **Regular:** all “rows” of a multi-dimensional array have the same size.
  - **Homogeneous:** all elements have the same type.

Regular arrays

In Python and F#, we can have lists of lists with irregular shapes:

```
>>> a = [[1,2,3], [4]]
>>> len(a)
2
>>> len(a[0])
3
>>> len(a[1])
1
```

- Such structures are **irregular**, and outside today's topic.
- What we will discuss is more similar to NumPy arrays.

So what's wrong with C arrays

We can declare an $n \times m$ array as

```
double A[n][m];
```

And then we can index it with for example `A[1][2]`. Easy!

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But there are many problems with built-in arrays:

- They decay to pointers in many situations.
- They cannot be passed to a function without losing their size.
- They cannot be returned from a function at all.
- **They are not values!**

Let's build our own arrays

- C as a *language* does not have useful dynamic arrays.
- But C does have useful support for *dynamic memory allocation*.
- So let's build our own arrays!

Constructing a dynamic array in C

- Use `malloc()` or `calloc()` to obtain a block of memory with room for enough *bytes* to fit the array we need.
- We can view these functions as allocating an "array of bytes", which we can then *interpret* as arrays of some other type.

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- **How much memory do we allocate?** An x-element array needs x`*sizeof(t)` bytes, where `t` is the element type (`int`, `double`, etc).

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Questions:

- **How much memory do we allocate?** An x-element array needs x`*sizeof(t)` bytes, where `t` is the element type (`int`, `double`, etc).
- **How do we lay out the array in memory?** That's a more open question...

Different allocating functions

malloc

Allocates a block of memory of a given size. Accessing uninitialised memory is undefined behaviour (E.g. don't do it)

calloc

Exactly the same as malloc, except that the memory is initialised the zero

realloc

Takes an already allocated block of memory and resizes it. No new initialisation takes place (both a blessing and a curse)

Note that use of realloc is often discouraged unless managed correctly, but its worth mentioning here as you will see it online.

What you take, you must give back

- Allocating memory means you claim it, no one else can use it.
- *Eventually* the OS will step in and clear it up for you, but depending on that is seen as **VERY BAD** practice.
- Submitting code that does this is seen as something to be penalised.

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- *Eventually* the OS will step in and clear it up for you, but depending on that is seen as **VERY BAD** practice.
- Submitting code that does this is seen as something to be penalised.
- Always always always, free any allocated memory
- use the `free(ptr)` command to free allocated memory, as pointed to by the given pointer
- You can test your program using `valgrind`

Why discourage realloc

- Consider the following code:
- `int *ptr = malloc(12);`

Why discourage realloc

- Consider the following code:
- `int *ptr = malloc(12);`
- If this fails then no memory is allocated. The pointer returned by malloc will be NULL, so we can detect this, but don't need to free anything.
- But now consider if the above was followed by:
- `ptr = realloc(ptr, 16);`
- If this fails then no memory is allocated and the pointer is again returned as NULL. But now we've lost the pointer to that first `malloc`, and that still needs free'd.

The idea

```
int* arr = malloc(12); // reserve 12 bytes
```

- Suppose `malloc()` returns the address 1000.
- When we do `arr[i]`, C computes the address $1000 + \texttt{i} \times \texttt{sizeof(int)}$ and reads an `int` (four bytes) from that address.
  - `&arr[0]`: 1000
  - `&arr[1]`: 1004
  - `&arr[2]`: 1008
- (Recall that `&x` means “the address of `x`”.)

One-dimensional arrays in C

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

int main(void) {
  int size = 10;
  int *arr = malloc(size * sizeof(int));

  printf("&arr: %p\n", (void*)&arr);
  printf("arr:  %p\n", (void*)arr);

  for (int i = 0; i < size; i++) {
    arr[i] = i*2;
    printf("&arr[%d]: %p ", i, (void*)&arr[i]);
    printf("arr[%d]: %d\n", i, arr[i]);
  }

  free(arr);
}
```

```
$ gcc 1darray.c -o 1darray
$ ./1darray
&arr: 0x7ffee169ba80
arr:  0x1bb42a0
&arr[0]: 0x1bb42a0 arr[0]: 0
&arr[1]: 0x1bb42a4 arr[1]: 2
&arr[2]: 0x1bb42a8 arr[2]: 4
&arr[3]: 0x1bb42ac arr[3]: 6
&arr[4]: 0x1bb42b0 arr[4]: 8
&arr[5]: 0x1bb42b4 arr[5]: 10
&arr[6]: 0x1bb42b8 arr[6]: 12
&arr[7]: 0x1bb42bc arr[7]: 14
&arr[8]: 0x1bb42c0 arr[8]: 16
&arr[9]: 0x1bb42c4 arr[9]: 18
```

Multi-dimensional arrays

- Machines (and C) provide a *one-dimensional memory (or index) space*.
- When we want multi-dimensional arrays (and we do!) we need to specify a *mapping* between our desired multi-dimensional space and the machine's single-dimensional space.

This is an *index function*.

Index functions

An index function maps a d-dimensional index to a single-dimensional index.

The type of index functions

$$I : \mathbb{N}^d \to \mathbb{N}$$

Index functions are not necessarily literal C functions, but a *conceptual* description of how the array is laid out in memory.

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Inverse index functions

$$I^{-1} : \mathbb{N} \rightarrow \mathbb{N}^d$$

$$\begin{pmatrix} 11 & 12 & 13 & 14 \\ 21 & 22 & 23 & 24 \\ 31 & 32 & 33 & 34 \end{pmatrix}$$

How do we lay out this matrix in memory?

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Row-major order: where elements of each *row* are contiguous in memory:

11	12	13	14	21	22	23	24	31	32	33	34

with index function

$$(i, j) \mapsto i \times 4 + j$$

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Column-major order: where elements of each *column* are contiguous in memory:

11	21	31	12	22	32	13	23	33	14	24	34

with index function

$$(i, j) \mapsto j \times 3 + i$$

Two-dimensional index functions for $n \times m$ arrays

Row-major indexing

$$(i, j) \mapsto i \times m + j$$

Column-major indexing

$$(i, j) \mapsto j \times n + i$$

Intuition:

- Row-major indexing first *skips* i rows each comprising m elements, then jumps j elements into the row we reach.
- This is why n (the number of rows) is not used for row-major indexing.

Column-major has same intuition, but we skip size-n columns instead.

Two-dimensional arrays in C

$$\begin{pmatrix} 11 & 12 & 13 & 14 \\ 21 & 22 & 23 & 24 \\ 31 & 32 & 33 & 34 \end{pmatrix}$$

```
int *A =
  malloc(3*4*sizeof(int));
A[0] = 11; // first row
A[1] = 12; // first row
A[2] = 13; // first row
A[3] = 14; // first row
A[4] = 21; // second row
...
A[11] = 34;
```

```
int *A =
  malloc(3*4*sizeof(int));
A[0] = 11; // first col
A[1] = 21; // first col
A[2] = 31; // first col
A[3] = 12; // second col
A[4] = 22; // second col
...
A[11] = 34;
```

Index functions as C functions

```
int idx2_rowmajor(int n, int m, int i, int j) {
  return i * m + j;
}

int idx2_colmajor(int n, int m, int i, int j) {
  return j * n + i;
}
```

Useful if you get confused when writing index calculations by hand (I often do!)

Careful!

Consider indexing the 3×4 array from before with the expression

```
A[idx2_rowmajor(n, m, 2, 5)].
```

- Trying to access index $(2, 5)$—conceptually out of bounds.
- Index function translates to the flat index $2 \times 3 + 5 = 11$.
- This is *in-bounds* for the 12-element flat array we use to represent our matrix!
- Our program will not crash, but this is probably a bug.

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- This is *in-bounds* for the 12-element flat array we use to represent our matrix!
- Our program will not crash, but this is probably a bug.

```
int idx2_rowmajor(int n, int m, int i, int j) {
  assert(i >= 0 && i < n);
  assert(j >= 0 && j < m);
  return i * m + j;
}
```

Higher dimensions

For a d-dimensional row-major array of shape $n_0 \times \cdots \times n_{d-1}$, the index function where p is a d-dimensional index point is

$$p \mapsto \sum_{0 \leq i < d} p_i \times \prod_{i < j < d} n_j$$

where p_i gets the ith coordinate of p, and the product of an empty series is 1.

Intuition: p_i tells us how many "subarrays" of size $n_{i+1} \ldots \times \ldots n_{d-1}$ we need to skip.

Example: four-dimensional indexing

Suppose we have a row-major array of shape

$$n_0 \times n_1 \times n_2 \times n_3$$

and we wish to compute the flat index of element position

$$(p_0, p_1, p_2, p_3)$$

We then have to sum these terms where the *strides* s_i depend on the array size:

$$\begin{array}{rl} & p_0 \times s_0 \\ + & p_1 \times s_1 \\ + & p_2 \times s_2 \\ + & p_3 \times s_3 \end{array}$$

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$$\begin{array}{ll} & p_0 \times n_1 \times n_2 \times n_3 \\ + & p_1 \times n_2 \times n_3 \\ + & p_2 \times n_3 \\ + & p_3 \times 1 \end{array}$$

The stride s_i is the product $\prod_{i<j<4} n_j$ of the array size after dropping the first $i+1$ dimensions.

Size passing

Since we represent arrays as the address of their first element, we must manually pass along the size when we call a function with an array.

```
double sumvec(int n, const double *vector) {
  double sum = 0;
  for (int i = 0; i < n; i++) {
    sum += vector[i];
  }
  return sum;
}
```

As usual: C will not protect us if we pass the wrong size. Be careful.

Slicing

- When using row-major order, the elements of each row are adjacent in memory.
- This allows us to perform efficient *slicing*, by taking the address of the first element in a row.

```
void sumrows(int n, int m,
             const double *matrix, double *vector) {
  for (int i = 0; i < n; i++) {
    vector[i] = sumvec(m, &matrix[i*m]);
  }
}
```

Conclusions

- C's built-in arrays are suitable only for small arrays, typically of static size.
- Dynamic allocation can create single-dimensional dynamic arrays on the heap.
- We can represent multi-dimensional arrays as single-dimensional arrays, by specifying an index function.
- Careful when indexing these home-made arrays—the C language is not much help.

Arrays

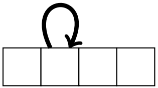
Locality of reference

Locality

Principle of locality

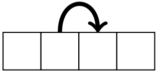
Programs tend to access data located near that which was accessed recently.

Temporal locality



Accessing data that was accessed recently.

Spatial locality



Accessing data that is close to data that was accessed recently.

- **General principles** — definition of "close" depends on the exact form of storage.
  - E.g. addresses for memory.

Locality example

```c
double sum = 0;
for (int i = 0; i < n; i++) {
  sum += a[i];
}
```

Data references

- References array elements in succession (*stride* of 1).

Locality example

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- References variable `sum` each iteration.

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Instruction references

- Executes instructions in sequence.

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- Executes instructions in sequence. **Spatial locality.**
- Cycles through loop repeatedly.

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Instruction references

- Executes instructions in sequence. **Spatial locality.**
- Cycles through loop repeatedly. **Temporal locality.**

Code as it's normally written has good locality by default, so we tend to focus only on *data locality*.

C array layout

```
int A[M][N];
```

To represent multi-dimensional arrays, C uses *row major order*.

Main consequence

- Rows are contiguous in memory.

Example

$$\begin{pmatrix} 11 & 12 & 13 & 14 \\ 21 & 22 & 23 & 24 \\ 31 & 32 & 33 & 34 \end{pmatrix}$$

is represented as

11	12	13	14	21	22	23	24	31	32	33	34

Implications

- `A[i][j]` and `A[i][j+1]` are adjacent.
- `A[i][j]` and `A[i+1][j]` are distant.

Eyeballing locality

Being able to glance at code and get a qualitative sense of its locality properties is a key skill for a programmer.

Does this function have good locality with respect to array `A`?

```
int sumrows(int A[M][N]) {
    int sum = 0;

    for (int i = 0; i < M; i++)
        for (int j = 0; j < N; j++)
            sum += A[i][j];
    return sum;
}
```

Does this function have good locality with respect to array `A`?

```
int sumcols(int A[M][N]) {
    int sum = 0;

    for (int j = 0; j < N; j++)
        for (int i = 0; i < M; i++)
            sum += A[i][j];
    return sum;
}
```

Transforming code for better locality

Can we permute the loops of this function such that we are accessing the memory of array `A` with a stride of 1?

```
int sum3d(int A[L][M][N]) {
    int sum = 0;

    for (int i = 0; i < M; i++)
        for (int j = 0; j < N; j++)
            for (int k = 0; k < L; k++)
                sum += A[k][i][j];
    return sum;
}
```

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        for (int j = 0; j < N; j++)
            for (int k = 0; k < L; k++)
                sum += A[k][i][j];
    return sum;
}
```

Yes: place them in order `k`, `i`, `j`.