Programming in C

Lecture 6: The Memory Hierarchy and Cache Optimization

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Three Simple C Functions

```
void increment_every(int *}array)
  for (int i = 0; i < BIG_NUMBER; i += 1) {
    array[i] = 0;
}
void increment_8th(int *array) {
  for (int i = 0; i < BIG_NUMBER; i += 8)
    array[i] = 0;
}
void increment_16th(int *array) {
  for (int i = 0; i < BIG_NUMBER; i += 16)
    array[i] = 0;
}
```

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- Which runs faster?

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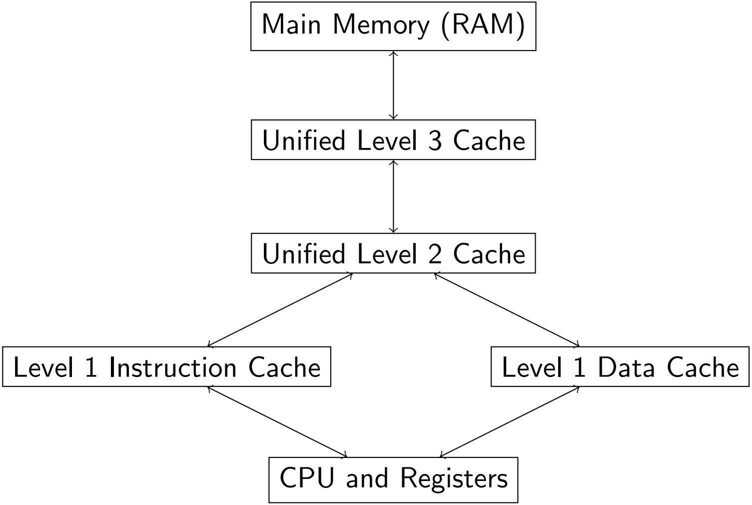
- Which runs faster?
- . . . and by how much?

The Memory Hierarchy



Latencies in the Memory Hierarchy

Access Type	Cycles	Time	Human Scale
L1 cache reference	≈4	1.3 ns	1s
L2 cache reference	≈10	4 ns	3s
L3 cache reference, unshared	≈40	13 ns	10s
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- Accesses to main memory are *slow*
- This can dominate performance!

How Caches Work

When a CPU looks up an address. . . :

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   3.2 The address/value pair is then stored in the cache
   3.3 . . . along with the next 64 bytes (typically) of memory
   3.4 This is a *cache line* or *cache block*

Locality: Taking advantage of caching

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- This is the *principle of locality*
- Performance engineering involves redesigning data structures to take advantage of locality.

Pointers Are Expensive

Consider the following Java linked list implementation

```
class List<T> {
  public T head;
  public List<T> tail;

  public List(T head, List<T> tail) {
    this.head = head;
    this.tail = tail;
  }
}
```

Pointers Are Expensive

It corresponds to the following C code:

```
typedef struct List* list_t;
struct List {
  void *head;
  list_t tail;
};
list_t list_cons(void *head, list_t tail) {
  list_t result = malloc(sizeof(struct list));
  r->head = head;
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- We use `void *` for genericity, but this introduces pointer indirections.
- This can get expensive!

Specializing the Representation

Suppose we use a list at a `Data *` type:

```
struct data {
  int i;
  double d;
  char c;
};
typedef struct data Data;

struct List {
  Data *head;
  struct List *tail;
};
```

Technique #1: Intrusive Lists

We can try changing the list representation to:

```
typedef struct intrusive_list ilist_t;
struct intrusive_list {
  Data head;
  ilist_t tail;
};
ilist_t ilist_cons(Data head, ilist_t tail) {
  list_t result = malloc(sizeof(struct intrusive_list));
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- The indirection in the head is removed
- But we had to use a specialized representation
- Can no longer use generic linked list routines

Technique #2: Lists of Structs to Arrays of Structs

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4. This decreases data density, and increases *cache miss rate*
5. Replace `ilist_t` with `Data[]`!

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We can try changing the list representation to:

```
Data *iota_array(int n) {
  Data *a = malloc(n * sizeof(Data));
  for (int i = 0; i < n; i++) {
    a[i].i = i;
    a[i].d =  1.0;
    a[i].c = 'x';
  }
  return a;
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- No longer store tail pointers
- Every element comes after previous element in memory
- Can no longer incrementally build lists
- Have to know size up-front

Technique #3: Arrays of Structs to Struct of Arrays

Suppose we have an operation

```
struct data {
  int i;
  double d;
  char c;
};
typedef struct data Data;

void traverse_array(int n, Data *a) {
  for (int i = 0; i < n; i++)
    a[i].c += 'y';
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- This means only 4 characters in each cache line. . .
- Optimally, 64 characters fit in each cache line. . .

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```
typedef struct datavec *DataVec;
struct datavec {
  int *is;
  double *ds;
  char *cs;
};
```

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typedef struct datavec *DataVec;
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```

- Instead of storing an array of structures...

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- Instead of storing an array of structures...
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```

- Instead of storing an array of structures. . .
- We store a struct of arrays
- Now traversing just the cs is easy

Technique #3: Traversing Struct of Arrays

```c
void traverse_datavec(int n, DataVec d) {
  char *a = d->cs;
  for (int i = 0; i < n; i++) {
    a[i] += 'y';
  }
}
```

Technique #3: Traversing Struct of Arrays

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void traverse_datavec(int n, DataVec d) {
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- To update the characters...

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- Just iterate over the character...
- Higher cache efficiency!

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- Caching make *locality assumption*
- Making this assumption true requires careful design
- Substantial code alterations can be needed
- But can lead to major performance gains