What if we have a large group of inter-related types?

For example, documents in a bibliography.

For each document, we have a reference.

But some documents are papers, while others are books.

Some papers are conference papers, while others are journal papers.

And some books are textbooks, while others may be part of a series.

Type Hierarchy Implies Structural Inclusion Relations

The basic type is a reference_t.
It has an author_list, a title, and a year of publication.

To organize references, we include a double_list_t (at the start of the struct).

The reference is shown as a child or sub-type of the double_list_t.

The result is called a type hierarchy (or, in other languages, a class hierarchy).

Example: A Bibliographic Type Hierarchy
Unrelated Types Sometimes Have Similar Fields

These are similar: books have ISBN numbers, as do published conference proceedings. But the fields are not shared (neither type in an ancestor of the other).

Structures Include Their Parent Type at the Start

Omitting typedefs, we write...

```c
struct double_list_t {
    double_list_t* prev;
    double_list_t* next;
};
struct reference_t {
    double_list_t link;
    char* author_list;
    char* title;
    int32_t year;
};
```

A Book’s First Field is a Reference

And, for books,

```c
struct book_t {
    reference_t ref;
    char* publisher;
    char* address;
    uint64_t ISBN;
};
```

Pointers Can Safely Be Cast to Ancestor Pointers

What does a book really look like in memory?

Notice that

- a `book_t*` also
- points to a `reference_t`
- and to a `double_list_t`

It is SAFE to cast pointers to pointers of any ancestor type.
How Can We Print Citations for All References?

Say we have a function

```c
void print_citation (reference_t* ref);
```

that prints a citation for a reference.

We want to print citations for all references in a bibliography (a sentinel):

```c
static double_list_t biblio;
```

How can we accomplish this task?

---

Loop Over All Elements, Cast Explicitly, and Call

Let's do it directly this time...

```c
double_list_t* elt;
for (elt = biblio.next; &biblio != elt; elt = elt->next) {
    print_citation ((reference_t*)elt);
}
```

---

All Elements of Bibliography Start with a Reference

Note that a given element of biblio may not be a reference.

So how is casting acceptable?

The element may also be a paper, a book, an article, a conference papers, a textbook, or a book from a series.

But all of them start with a `reference_t`!

(`reference_t` is the ancestor of all of the types.)

---

Can We Cast to Pointers of Subtypes?

So that's nice.

Unfortunately, in reality,
- citations for books are printed differently
- than citations for conference papers and
- differently than citations for journal articles.

What can we do?

Can we cast from `reference_t*` to `book_t*`?
Or to `article_t*`? (to subtypes in general?)
Cannot Know What’s in Memory After a Reference

In other words, given only a reference_t*, can we safely cast to a subtype pointer? Absolutely not!
Without additional information, we have no way to know what’s in memory after the reference_t.

Separating the Bibliography by Type is Cumbersome

So … keep a bibliography for each type? No. Separate lists are unattractive.
Why bother to have a type hierarchy
- if we have to operate separately
- on every type
- for every operation?
Instead, add dynamic type information.

Record Actual Type in a New Field

struct reference_t {
    double_list_t link;
    char* author_list;
    char* title;
    int32_t year;
    int32_t type;
};

Use switch to Handle Each Subtype Separately

Then, in print_citation...

```c
void print_citation (reference_t* ref) {
    switch (ref->type) {
        case TYPE_PAPER: // ...
            break;
        case TYPE_BOOK: // ...
            break;
        // ...
    }
}
```
Perhaps Useful to Write as Separate Functions

But maybe the citation printing code
- is lengthy, or
- is useful elsewhere.
In that case, write...

```c
print_paper_citation(paper_t* paper);
print_book_citation(book_t* book);
and so forth.
```

Each Case is Then Just a Function Call

Then, in `print_citation`...
```c
switch (ref->type) {
    case TYPE_PAPER:
        print_paper_citation((paper_t*)ref);
        break;
    // ...
}
```

A Function Pointer Has a Specific Signature

But if every case is just a function call...
```c
...why not just add a function pointer to reference_t instead?
```
One problem: the functions don't have the same signatures...
```c
print_paper_citation(paper_t* paper);
print_book_citation(book_t* book);
```

Solution: Use a Pointer to the Known Ancestor Type

Let's
- replace all pointers with `reference_t*`
- and cast to the appropriate type in each function (we know it's safe in each case).
For example,
```c
print_book_citation(reference_t* ref) {
    book_t* book = (book_t*)ref;
    // ...
```
Add a Function Pointer for Printing a Citation

```c
struct reference_t {
    double_list_t link;
    char* author_list;
    char* title;
    int32_t year;
    void (*print_citation)(reference_t* ref);
};
```

Function Pointers Allow Partial Customization

In any `paper_t`, the `print_citation` field points to `print_paper_citation`.

Similarly, in any `book_t`, the `print_citation` field points to `print_book_citation`.

And so forth.

Note that we do not have to specialize

- for example, we might choose to have
  - `print_citation` point to `print_book_citation` in any `textbook_t`.

To Print All, Loop Over All Elements and Call

Now to print our bibliography...

```c
double_list_t* elt;
reference_t* ref;
for (elt = biblio.next; elt && biblio != elt; elt = elt->next) {
    ref = (reference_t*)elt;
    (*ref->print_citation)(ref);
}
```

Cost Increases if We Customize Many Functions

As you saw,

- the code is a little cleaner
- but allows customization of functionality by type.

What's the cost?

One pointer per structure variable ...

... per function customized.

Can we reduce this cost?
Instead, Use One Table of Function Pointers per Type

What if, instead,
◦ for each type
◦ we create a table (a struct)
◦ filled with function pointers?
We only need one such table per type, NOT one table per variable.
And one pointer per variable—to the variable’s type’s table of function pointers.

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Virtual Function Table Pointer Refers to Table for Type

Let’s call the table pointer vtab.
And place it at the start of the structure, so that we can always find it.
Every book’s vtab points to the table for books.
Every reference’s vtab points to the table for references.

“A virtual function table.”

Calling a Virtual Function Requires Two Memory Reads

Two loads followed by a call (JSRR, for example), instead of just a call.
That’s the more significant cost.

You may want to try converting our bibliography printing code into LC-3 assuming that vtab is at the start of each structure (before the double_list_t).
Choose some non-zero index for print_citation in the table to make it interesting (the index must be a constant, of course).