CSCE 230J
Computer Organization

Linking

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Giving credit where credit is due

- **Most of slides for this lecture are based on slides created by Drs. Bryant and O'Hallaron, Carnegie Mellon University.**
- **I have modified them and added new slides.**

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Topics

- Static linking
- Object files
- Static libraries
- Loading
- Dynamic linking of shared libraries

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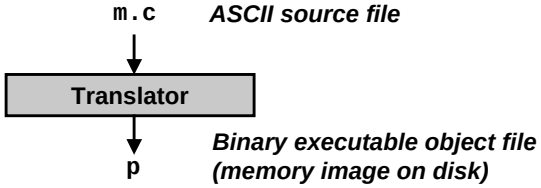
A Simplistic Program Translation Scheme



Problems:
- **Efficiency: small change requires complete recompilation**
- **Modularity: hard to share common functions (e.g. `printf`)**

Solution:
- ***Static linker (or linker)***

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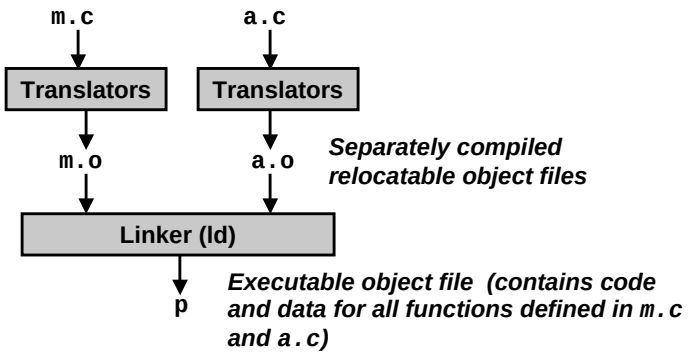
A Better Scheme Using a Linker



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Translating the Example Program

Compiler driver **coordinates all steps in the translation and linking process.**

- **Typically included with each compilation system (e.g., `gcc`)**
- **Invokes preprocessor (`cpp`), compiler (`cc1`), assembler (`as`), and linker (`ld`).**
- **Passes command line arguments to appropriate phases**

Example: create executable `p` from `m.c` and `a.c`:

```
bass> gcc -O2 -v -o p m.c a.c
cpp [args] m.c /tmp/cca07630.i
cc1 /tmp/cca07630.i m.c -O2 [args] -o /tmp/cca07630.s
as [args] -o /tmp/cca076301.o /tmp/cca07630.s
<similar process for a.c>
ld -o p [system obj files] /tmp/cca076301.o /tmp/cca076302.o
bass>
```

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What Does a Linker Do?

Merges object files

- Merges multiple relocatable (.o) object files into a single executable object file that can be loaded and executed by the loader.

Resolves external references

- As part of the merging process, resolves external references.
  - *External reference*: reference to a symbol defined in another object file.

Relocates symbols

- Relocates symbols from their relative locations in the `.o` files to new absolute positions in the executable.
- Updates all references to these symbols to reflect their new positions.
  - References can be in either code or data
    - » code: `a();  /* reference to symbol a */`
    - » data: `int *xp=&x;  /* reference to symbol x */`

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Why Linkers?

Modularity

- Program can be written as a collection of smaller source files, rather than one monolithic mass.
- Can build libraries of common functions (more on this later)
  - e.g., Math library, standard C library

Efficiency

- Time:
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.
- Space:
  - Libraries of common functions can be aggregated into a single file...
  - Yet executable files and running memory images contain only code for the functions they actually use.

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Executable and Linkable Format (ELF)

- Standard binary format for object files
- Derives from AT&T System V Unix
  - Later adopted by BSD Unix variants and Linux
- One unified format for
  - Relocatable object files (`.o`),
  - Executable object files
  - Shared object files (`.so`)
- Generic name: ELF binaries
- Better support for shared libraries than old `a.out` formats.

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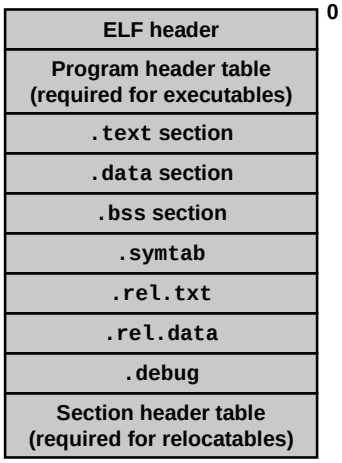
ELF Object File Format

- Elf header
  - Magic number, type (.o, exec, .so), machine, byte ordering, etc.
- Program header table
  - Page size, virtual addresses memory segments (sections), segment sizes.
- `.text` section
  - Code
- `.data` section
  - Initialized (static) data
- `.bss` section
  - Uninitialized (static) data
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space



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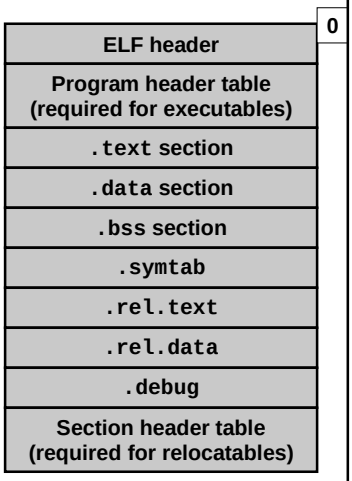
ELF Object File Format (cont)

`.symtab` section
- Symbol table
- Procedure and static variable names
- Section names and locations

`.rel.text` section
- Relocation info for `.text` section
- Addresses of instructions that will need to be modified in the executable
- Instructions for modifying.

`.rel.data` section
- Relocation info for `.data` section
- Addresses of pointer data that will need to be modified in the merged executable

`.debug` section
- Info for symbolic debugging (`gcc -g`)



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Example C Program

m.c

```
int e=7;

int main() {
  int r = a();
  exit(0);
}
```

a.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

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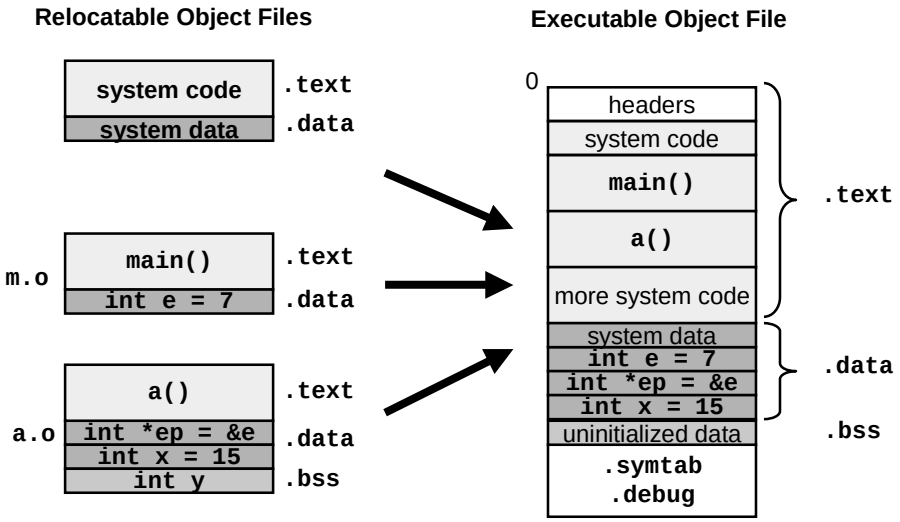
Merging Relocatable Object Files into an Executable Object File



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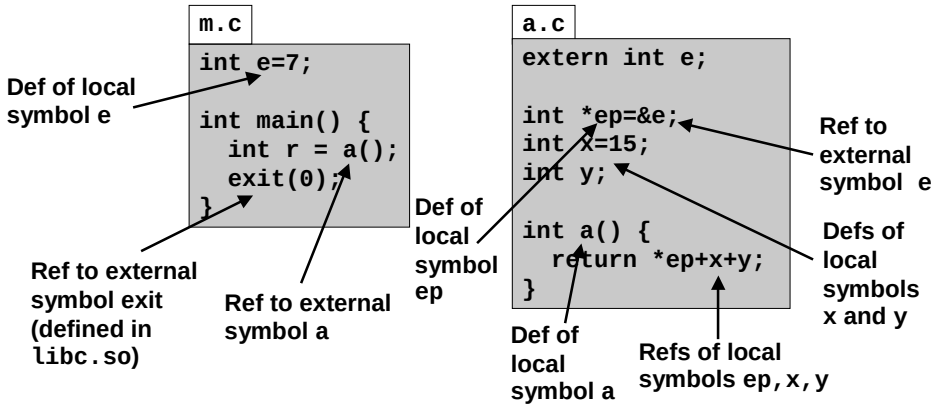
Relocating Symbols and Resolving External References

- ***Symbols*** **are lexical entities that name functions and variables.**
- **Each symbol has a *value* (typically a memory address).**
- **Code consists of symbol *definitions* and *references*.**
- **References can be either *local* or *external*.**



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m.o Relocation Info

m.c

```
int e=7;

int main() {
  int r = a();
  exit(0);
}
```

```
Disassembly of section .text:

00000000 <main>: 00000000 <main>:
   0:   55              pushl  %ebp
   1:   89 e5           movl   %esp,%ebp
   3:   e8 fc ff ff ff  call   4 <main+0x4>
                        4: R_386_PC32   a
   8:   6a 00           pushl  $0x0
   a:   e8 fc ff ff ff  call   b <main+0xb>
                        b: R_386_PC32   exit
   f:   90              nop
```

```
Disassembly of section .data:

00000000 <e>:
   0:   07 00 00 00
```

source: objdump

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a.o Relocation Info (.text)

a.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

```
Disassembly of section .text:

00000000 <a>:
   0:   55              pushl  %ebp
   1:   8b 15 00 00 00  movl   0x0,%edx
   6:   00
                        3: R_386_32     ep
   7:   a1 00 00 00 00  movl   0x0,%eax
                        8: R_386_32     x
   c:   89 e5           movl   %esp,%ebp
   e:   03 02           addl   (%edx),%eax
  10:   89 ec           movl   %ebp,%esp
  12:   03 05 00 00 00  addl   0x0,%eax
  17:   00
                        14: R_386_32    y
  18:   5d              popl   %ebp
  19:   c3              ret
```

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a.o Relocation Info (.data)

a.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

```
Disassembly of section .data:

00000000 <ep>:
   0:   00 00 00 00
                        0: R_386_32     e
 00000004 <x>:
   4:   0f 00 00 00
```

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Executable After Relocation and External Reference Resolution (.text)

```
08048530 <main>:
 8048530:       55              pushl  %ebp
 8048531:       89 e5           movl   %esp,%ebp
 8048533:       e8 08 00 00 00  call   8048540 <a>
 8048538:       6a 00           pushl  $0x0
 804853a:       e8 35 ff ff ff  call   8048474 <_init+0x94>
 804853f:       90              nop

08048540 <a>:
 8048540:       55              pushl  %ebp
 8048541:       8b 15 1c a0 04  movl   0x804a01c,%edx
 8048546:       08
 8048547:       a1 20 a0 04 08  movl   0x804a020,%eax
 804854c:       89 e5           movl   %esp,%ebp
 804854e:       03 02           addl   (%edx),%eax
 8048550:       89 ec           movl   %ebp,%esp
 8048552:       03 05 d0 a3 04  addl   0x804a3d0,%eax
 8048557:       08
 8048558:       5d              popl   %ebp
 8048559:       c3              ret
```

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Executable After Relocation and External Reference Resolution(.data)

m.c

```
int e=7;

int main() {
  int r = a();
  exit(0);
}
```

a.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

```
Disassembly of section .data:

0804a018 <e>:
 804a018:       07 00 00 00

0804a01c <ep>:
 804a01c:       18 a0 04 08

0804a020 <x>:
 804a020:       0f 00 00 00
```

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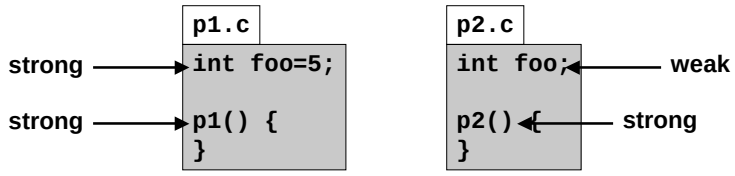
Strong and Weak Symbols

Program symbols are either strong or weak

- ***strong*: procedures and initialized globals**
- ***weak*: uninitialized globals**



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Linker's Symbol Rules

Rule 1. A strong symbol can only appear once.

Rule 2. A weak symbol can be overridden by a strong symbol of the same name.

- **references to the weak symbol resolve to the strong symbol.**

Rule 3. If there are multiple weak symbols, the linker can pick an arbitrary one.

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Linker Puzzles

`int x;` `p1() {}`	`p1() {}`	**Link time error: two strong symbols (p1)**
`int x;` `p1() {}`	`int x;` `p2() {}`	**References to x will refer to the same uninitialized int. Is this what you really want?**

`int x;`
`int y;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to x in p2 might overwrite y! Evil!

`int x=7;`
`int y=5;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to x in p2 will overwrite y! Nasty!

`int x=7;` `p1() {}`	`int x;` `p2() {}`	**References to x will refer to the same initialized variable.**

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

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Packaging Commonly Used Functions

How to package functions commonly used by programmers?

- **Math, I/O, memory management, string manipulation, etc.**

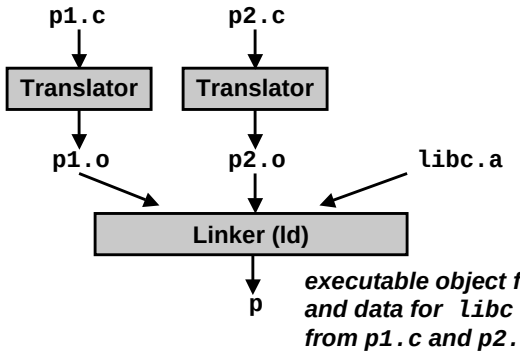
Awkward, given the linker framework so far:

- **Option 1: Put all functions in a single source file**
  - **Programmers link big object file into their programs**
  - **Space and time inefficient**
- **Option 2: Put each function in a separate source file**
  - **Programmers explicitly link appropriate binaries into their programs**
  - **More efficient, but burdensome on the programmer**

Solution: *static libraries* (.a archive files)

- **Concatenate related relocatable object files into a single file with an index (called an archive).**
- **Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.**
- **If an archive member file resolves reference, link into executable.**

Static Libraries (archives)



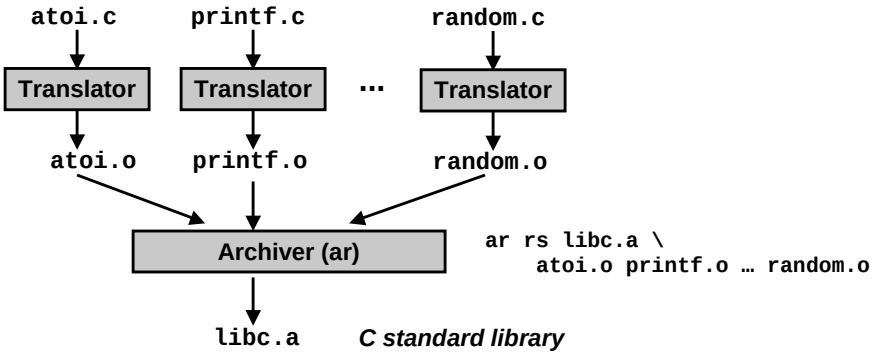
static library (archive) of relocatable object files concatenated into one file.

executable object file (only contains code and data for `libc` functions that are called from `p1.c` and `p2.c`)

Further improves modularity and efficiency by packaging commonly used functions [e.g., C standard library (`libc`), math library (`libm`)]

Linker selectively only the `.o` files in the archive that are actually needed by the program.

Creating Static Libraries



Archiver allows incremental updates:

- **Recompile function that changes and replace .o file in archive.**

Commonly Used Libraries

`libc.a` (the C standard library)

- **8 MB archive of 900 object files.**
- **I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math**

`libm.a` (the C math library)

- **1 MB archive of 226 object files.**
- **floating point math (sin, cos, tan, log, exp, sqrt, …)**

```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```

Using Static Libraries

Linker's algorithm for resolving external references:

- Scan .o files and .a files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new .o or .a file obj is encountered, try to resolve each unresolved reference in the list against the symbols in obj.
- If any entries in the unresolved list at end of scan, then error.

Problem:

- Command line order matters!
- Moral: put libraries at the end of the command line.

```
bass> gcc -L. libtest.o -lmine
bass> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

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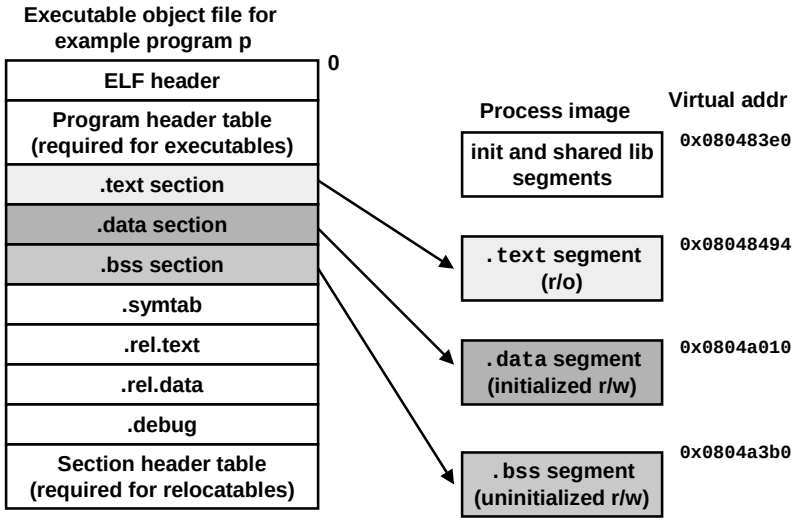
Loading Executable Binaries



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Shared Libraries

Static libraries have the following disadvantages:

- **Potential for duplicating lots of common code in the executable files on a filesystem.**
  - **e.g., every C program needs the standard C library**
- **Potential for duplicating lots of code in the virtual memory space of many processes.**
- **Minor bug fixes of system libraries require each application to explicitly relink**

Solution:

- ***Shared libraries* (dynamic link libraries, DLLs) whose members are dynamically loaded into memory and linked into an application at run-time.**
  - **Dynamic linking can occur when executable is first loaded and run.**
    - » **Common case for Linux, handled automatically by `ld-linux.so`.**
  - **Dynamic linking can also occur after program has begun.**
    - » **In Linux, this is done explicitly by user with `dlopen()`.**
    - » **Basis for High-Performance Web Servers.**
  - **Shared library routines can be shared by multiple processes.**

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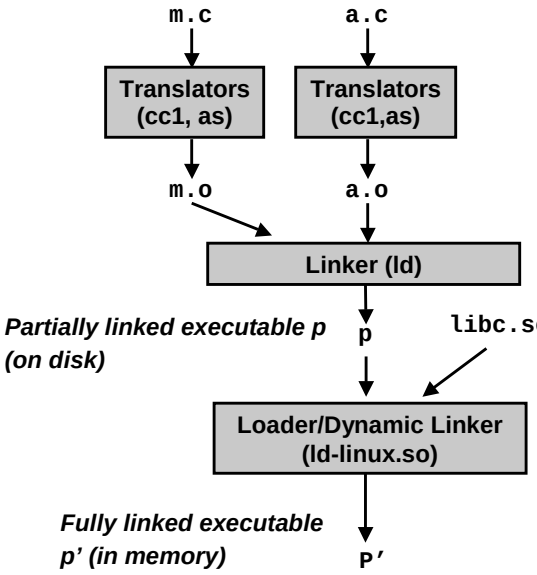
Dynamically Linked Shared Libraries



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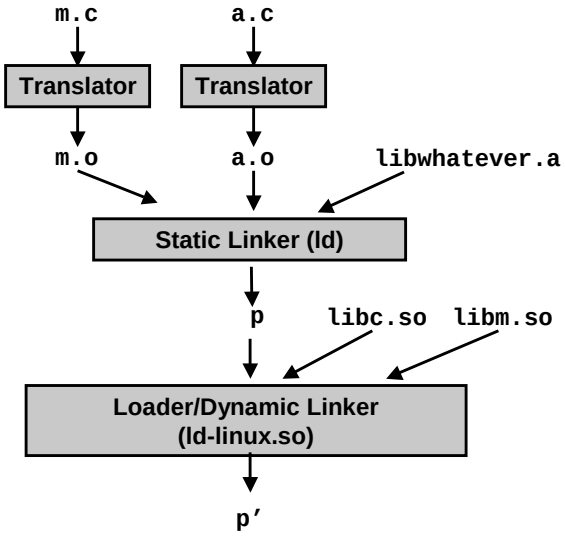
The Complete Picture



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