| 31 30 29 28 27 26 25 | 24 23 22 21 20 | 19 18 17 16 15 | 14 13 12 | 11 10 9 8 7 | 6 5 4 3 2 1 0 | |
|---|---|---|---|---|---|---|
| funct7 | rs2 | rs1 | funct3 | rd | opcode | R-type |
| imm[11:0] | | rs1 | funct3 | rd | opcode | I-type |
| imm[11:5] | rs2 | rs1 | funct3 | imm[4:0] | opcode | S-type |
| imm[12\|10:5] | rs2 | rs1 | funct3 | rd | opcode | B-type |
| imm[31:12] | | | | rd | opcode | U-type |
| imm[20\|10:1\|11\|19:12] | | | | rd | opcode | J-type |

**Zbb**: “Basic bit-manipulation” Extension

| 31 25 | 24 20 | 19 15 | 14 12 | 11 7 | 6 0 | |
|---|---|---|---|---|---|---|
| 0 1 0 0 0 0 0 | rs2 | rs1 | 1 1 1 | rd | 0 1 1 0 0 1 1 | ANDN |
| 0 1 0 0 0 0 0 | rs2 | rs1 | 1 1 0 | rd | 0 1 1 0 0 1 1 | ORN |
| 0 1 0 0 0 0 0 | rs2 | rs1 | 1 0 0 | rd | 0 1 1 0 0 1 1 | XNOR |
| 0 1 1 0 0 0 0 | 0 0 0 0 0 | rs1 | 0 0 1 | rd | 0 0 1 0 0 1 1 | CLZ |
| 0 1 1 0 0 0 0 | 0 0 0 0 1 | rs1 | 0 0 1 | rd | 0 0 1 0 0 1 1 | CTZ |
| 0 1 1 0 0 0 0 | 0 0 0 1 0 | rs1 | 0 0 1 | rd | 0 0 1 0 0 1 1 | CPOP |
| 0 0 0 0 1 0 1 | rs2 | rs1 | 1 1 0 | rd | 0 1 1 0 0 1 1 | MAX |
| 0 0 0 0 1 0 1 | rs2 | rs1 | 1 1 1 | rd | 0 1 1 0 0 1 1 | MAXU |
| 0 0 0 0 1 0 1 | rs2 | rs1 | 1 0 0 | rd | 0 1 1 0 0 1 1 | MIN |
| 0 0 0 0 1 0 1 | rs2 | rs1 | 1 0 1 | rd | 0 1 1 0 0 1 1 | MINU |
| 0 1 1 0 0 0 0 | 0 0 1 0 0 | rs1 | 0 0 1 | rd | 0 0 1 0 0 1 1 | SEXT.B |
| 0 1 1 0 0 0 0 | 0 0 1 0 1 | rs1 | 0 0 1 | rd | 0 0 1 0 0 1 1 | SEXT.H |
| 0 0 0 0 1 0 0 | 0 0 0 0 0 | rs1 | 1 0 0 | rd | 0 1 1 0 0 1 1 | ZEXT.H |
| 0 1 1 0 0 0 0 | rs2 | rs1 | 0 0 1 | rd | 0 1 1 0 0 1 1 | ROL |
| 0 1 1 0 0 0 0 | rs2 | rs1 | 1 0 1 | rd | 0 1 1 0 0 1 1 | ROR |
| 0 1 1 0 0 0 0 | shamt | rs1 | 1 0 1 | rd | 0 0 1 0 0 1 1 | RORI |
| 0 0 1 0 1 0 0 | 0 0 1 1 1 | rs1 | 1 0 1 | rd | 0 0 1 0 0 1 1 | ORC.B |
| 0 1 1 0 1 0 0 | 1 1 0 0 0 | rs1 | 1 0 1 | rd | 0 0 1 0 0 1 1 | REV8 |

| 31 30 29 28 27 26 25 | 24 23 22 21 20 | 19 18 17 16 15 | 14 13 12 | 11 10 9 8 7 | 6 5 4 3 2 1 0 | |
|---|---|---|---|---|---|---|
| funct7 | rs2 | rs1 | funct3 | rd | opcode | R-type |
| imm[11:0] | | rs1 | funct3 | rd | opcode | I-type |
| imm[11:5] | rs2 | rs1 | funct3 | imm[4:0] | opcode | S-type |
| imm[12\|10:5] | rs2 | rs1 | funct3 | rd | opcode | B-type |
| imm[31:12] | | | | rd | opcode | U-type |
| imm[20\|10:1\|11\|19:12] | | | | rd | opcode | J-type |

**Zor**: “Objective RISC” Extension 2

Unprivileged:

| 31 25 | 24 20 | 19 15 | 14 12 | 11 7 | 6 0 | | |
|---|---|---|---|---|---|---|---|
| 0 0 0 0 0 0 0 | zero | rs1 | 0 0 0 | rd | 0 0 0 1 0 1 1 | ALC | R |
| size[13:2] | | sp | 0 1 0 | rd | 0 0 0 1 0 1 1 | ALCI | I |
| 0 0 0 0 0 0 0 | zero | rs1 | 0 0 1 | rd | 0 0 0 1 0 1 1 | ALC.D | R |
| size[13:2] | | sp | 0 1 1 | rd | 0 0 0 1 0 1 1 | ALCI.D | I |
| 0 0 0 0 0 0 0 | zero | rs1 | 1 0 0 | rd | 0 0 0 1 0 1 1 | QSZ | R |
| 0 0 0 0 0 0 0 | zero | rs1 | 1 0 1 | rd | 0 0 0 1 0 1 1 | LEB | R |
| 0 0 0 0 0 0 0 | rs2 | rs1 | 1 1 0 | zero | 0 0 0 1 0 1 1 | CLR | R |
| | | | | | | | |

Machine Mode:

| 31 26 | 25 | 24 20 | 19 15 | 14 12 | 11 7 | 6 0 | | |
|---|---|---|---|---|---|---|---|---|
| 0 1 1 1 1 1 | 1 | rs2 | rs1 | 0 0 0 | rd | 1 1 1 0 0 1 1 | DTP | R |
| 1 0 1 1 1 1 | 1 | zero | rs1 | 0 0 0 | rd | 1 1 1 0 0 1 1 | PTD | R |
| 1 1 0 1 1 1 | 1 | zero | rs1 | 0 0 0 | rd | 1 1 1 0 0 1 1 | ITD | R |
| | | | | | | | | |

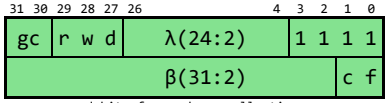
Misc:

| reg | alias | reg | alias |
|---|---|---|---|
| x0 | zero | x16 | a6 |
| x1 | ra | x17 | a7 |
| x2 | sp | x18 | s2 |
| x3 | gp (got) | x19 | s3 |
| x4 | tp | x20 | s4 |
| x5 | t0 | x21 | s5 |
| x6 | t1 | x22 | s6 |
| x7 | t2 | x23 | s7 |
| x8 | s0 | x24 | s8 |
| x9 | s1 | x25 | s9 |
| x10 | a0 | x26 | s10 |
| x11 | a1 | x27 | s11 |
| x12 | a2 | x28 | t3 |
| x13 | a3 | x29 | t4 |
| x14 | a4 | x30 | t5 |
| x15 | a5 | x31 | t6 |

| pseudo-instruction | implemented as |
|---|---|
| push imm | alci sp, imm |
| pop | lw/d sp, 4(sp) |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

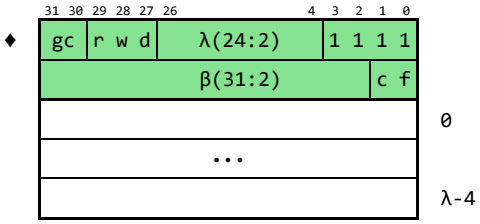
# OBJECTS

*Generic Header*

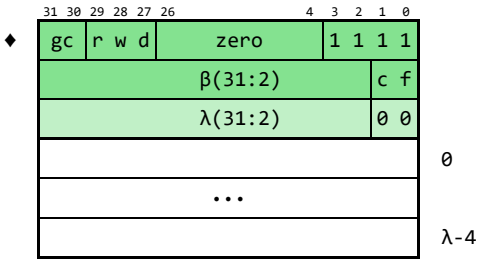



gc: reserved bits for garbage collection
r: readable
w: writable
d: data only (no pointers allowed)
λ: length of this object
β: current access barrier
f: is stack frame object?
c: color of stack frame if f = 1, else don't care

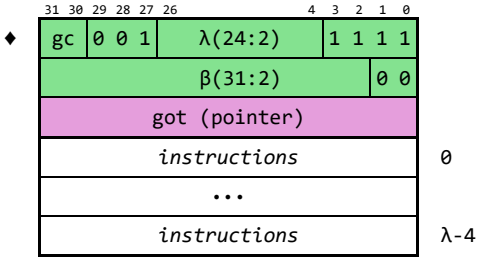
Ordinary



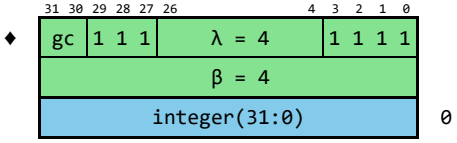

Long



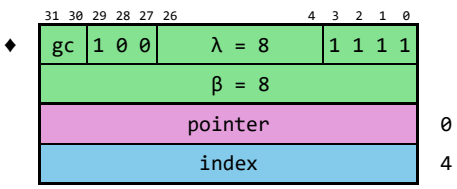

Executable




*Immediate (Primitive)*




*Immediate (Pointer)*

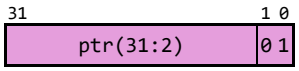



**Invariant 1:** data-only objects which are not readable and not writable are implicitly executable
**Invariant 2:** Objects with λ = 0 in their base-header have λ moved to the address following β

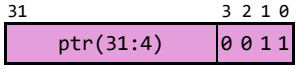
# POINTERS & DATA

**(in memory)**

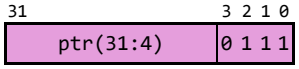
immediate (prim) pointer:



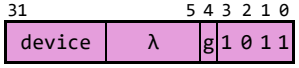

ordinary pointer

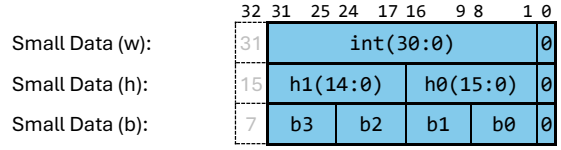



immediate (ptr) pointer:



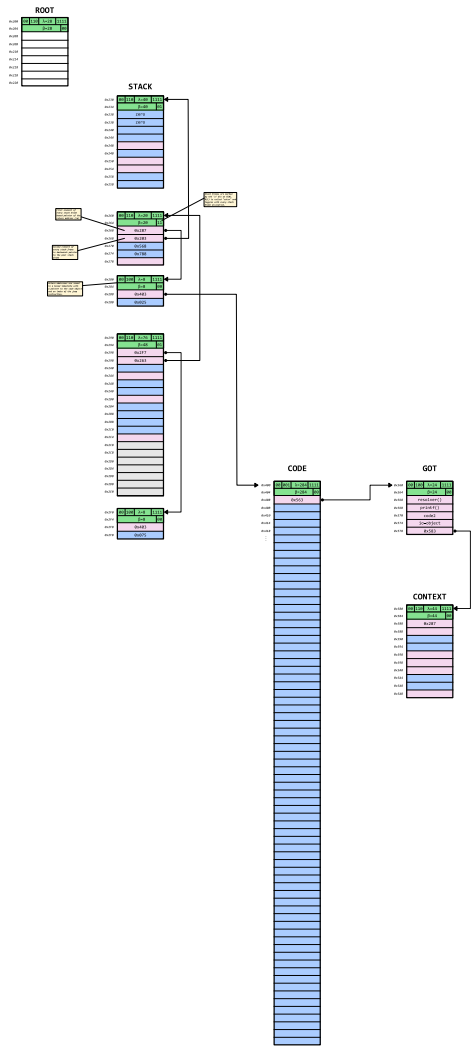

io pointer:



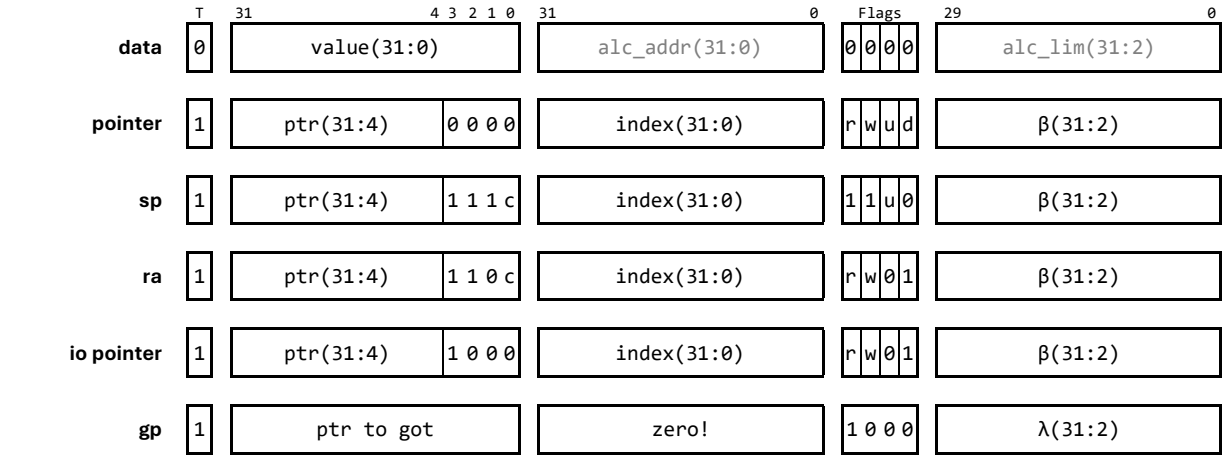

Allocate immediate primitive if:

- sw and rs(30) ≠ rs(31)
- sh at h1 and rs(14) ≠ rs(15)
- sb at b3 and (rs(7) = 1 or rs < 0)


ROOT
STACK
CODE
GOT
CONTEXT

# REGISTER FILE & PIPELINE

**Architectural Registers (x0-x31, alc-params):**




Tags:
**r** read access, **w** write access, **u** 0 when β = λ else 1, **d** data only

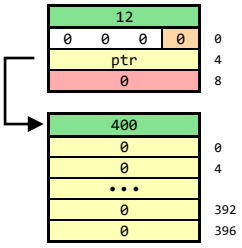
**Microarchitectural Registers:**

# OBJECT INITIALIZATION

## CLEAR ON ALC

```
struct foo {
    bool a = false;
    int  array[100];
    int  c = 0;
} bar;
```

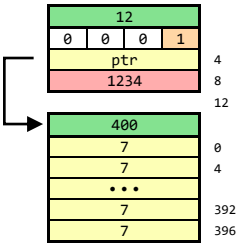
```
routine0:
  alci     s0, 12
.init0:
  clr      s0
  leb      t0, s0
  beq      zero,t0,.init0
  alci     t1, 400
.init1:
  clr      t1, zero
  leb      t0, t1
  beq      zero,t0,.init1
  sw       t1, 4(s0)
```




## INIT WITH DEFAULTS

```
struct foo {
    bool a = true;
    int  array[100];
    int  c = 1234;
} bar;
…
//forall
  bar->array[i] = 7;
```

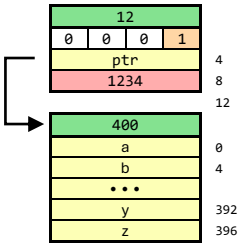
```
routine0:
  alci     s0, 12
  li       t1, 1
  sb       t1, 0(s0)
  alci     t2, 400
  sw       t2, 4(s0)
  li       t3, 1234
  sw       t3, 8(s0)

  li       t4, 7
.init1:
  clr      t2, t4
  leb      t5, t2
  beq      zero,t5,.init1
```




## DISALLOWED LAZY INIT

```
struct foo {
    bool a = true;
    int  array[100];
    int  c = 1234;
} bar;
…
bar->array = routine1();
```

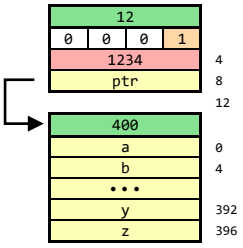
```
routine0:
  alci     s0, 12
  li       t1, 1
  sb       t1, 0(s0)
  li       t1, 1234
  sw       t1, 8(s0)
  ...
  jal      ra, routine1
  sw       a0, 4(s0)
```



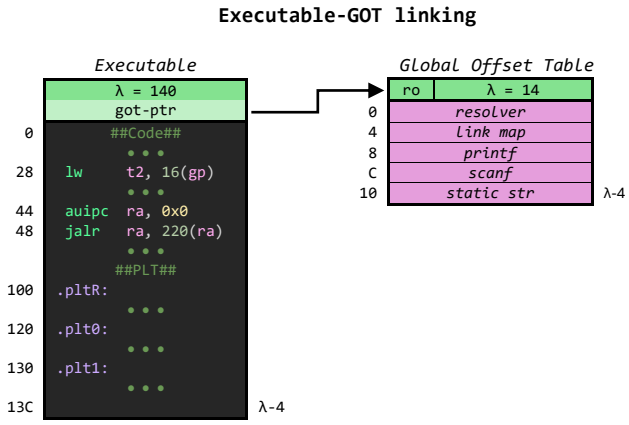

## ALLOWED LAZY INIT

```
struct foo {
    bool a = true;
    int  array[100];
    int  c = 1234;
} bar;
…
bar->array = routine1();
```

```
routine0:
  alci     s0, 12
  li       t1, 1
  sb       t1, 0(s0)
  li       t1, 1234
  sw       t1, 4(s0)
  ...
  jal      ra, routine1
  sw       a0, 8(s0)
```



# CODE SEGMENTATION




Code-Objects can only be exited via the procedure linkage table (plt) which uses entries of the global offset table (got). Upon creation of the code-object or on the first try to exit the code object, the supervisor puts the pointer to the target code-object into the global offset table, if (and only if) the source code-object is allowed to jump to that target.

**User Mode Instructions (Single Cycle)**

| Instruction | rd | rs1 | rs2 | cr | imm | Decision |
|---|---|---|---|---|---|---|
| lui | rd | --- | --- | - | imm | |
| auipc | rd | --- | --- | - | imm | |
| jal | rd | --- | sp | ● | imm | |
| | | | | | | |
| bcc | --- | rs1 | rs2 | - | imm | |
| | | | | | | |
| arithi | rd | rs1 | --- | - | imm | |
| arith | rd | rs1 | rs2 | - | --- | |
| | | | | | | |
| lb/bu/h/hu/w | rd | rs1 | --- | ● | imm | |
| | | | | | | |
| alc | rd | rs1 | sp | ● | --- | |
| alci | rd | --- | sp | ● | imm | |
| alc.d | rd | rs1 | sp | ● | --- | |
| alci.d | rd | --- | sp | ● | imm | |
| qsz | rd | rs1 | --- | - | --- | |
| clr | rs1 | rs1 | rs2 | - | --- | |
| leb | rd | rs1 | --- | - | --- | |
| | | | | | | |

**User Mode Instructions (Multi Cycle)**

| Instruction | rd | rs1 | rs2 | cr | imm | Decision |
|---|---|---|---|---|---|---|
| **jalr** | *rd* | *rs1* | --- | - | *imm* | |
| A jalr | rd | rs1 | sp | ● | imm | *always* |
| A lgt | got | rs1 | --- | - | --- | *always (instead of nop)* |
| | | | | | | |
| **sb/h/w** | --- | *rs1* | *rs2* | - | *imm* | |
| A sb/h/w | rs1 | rs1 | rs2 | ● | imm | *always* |
| a sb/h/w | rs1 | rs1 | rs2 | ● | imm | *needed if wdata gets boxed* |
| | | | | | | |

**Supervisor Mode Instructions:**

| Instruction | rd | rs1 | rs2 | cr | imm | Notes |
|---|---|---|---|---|---|---|
| dtp | rd | rs1 | --- | - | --- | *“data to pointer”, creates a pointer from data* |
| ptd | rd | rs1 | --- | - | --- | *“pointer to data”, extracts base address of pointer as data* |
| itd | rd | rs1 | --- | - | --- | *“index to data”, extracts index of pointer as data* |
| | | | | | | |
| | | | | | | |

# DOKUMENTATION: ELF-FILES

“Executable and Linkable Format”-Files bestehen mindestens aus einem Header, einer “Program Header Table” und einer “Section Header Table”. Im Header werden Informationen über das ELF-File selbst gespeichert, wie z.B. die Prozessorarchitektur, für welche das Programm kompiliert wurde und die Positionen der PHT und der SHT in Relation zum File-Anfang. In einem Program Header werden Informationen gespeichert, die dem Betriebssystem angeben, wie viele und welche Arten von virtuellen Seiten für dieses Programm benötigt werden. In einem Section Header wird angegeben, in welche Einzelteile das Programm zerlegt wurde und ob noch mehr Informationen über das Programm im ELF-File zu finden sind (z.B. für relocatable Programme).

## Daten

Statische Daten werden von einem Compiler über Assemblerdirektiven immer so in die `.data` bzw. `.rodata` Sektionen abgelegt, sodass sie in der Symboltabelle des ELF-Files immer als Objekt mit seiner Größe eindeutig erkennbar sind.

```
//C-Code
static char stringA[] = "hello world!";


#Resultierender Assembly-Code
.data

.type    stringA, @object
stringA: .asciz "hello world!"
.size    stringA, .-stringA


//Section Header Table im erzeugten ELF-File
Section Headers:
  [Nr] Name      Type      Address   Offset    Size      EntSize   Flags Link Info Align
       ...
  [ 5] .data     PROGBITS  00002010  000003b4  0000000d  00000000   WA     0    0    4
  [ 6] .rodata   PROGBITS  00002020  000003c4  0000000d  00000000    A     0    0    4
       ...

//Symbol Table im erzeugten ELF-File
Symbol table '.symtab' contains 60 entries:
   Num:  Value     Size Type    Bind   Vis      Ndx Name
       ...
    49: 00000000    13 OBJECT  LOCAL  DEFAULT    5 stringA
    50: 00000000    13 OBJECT  LOCAL  DEFAULT    6 stringB
       ...
```

```
//C-Code
static const char stringB[] = "hello world!";


#Resultierender Assembly-Code
.rodata

.type    stringB, @object
stringB: .asciz "hello world!"
.size    stringB, .-stringB
```

Ein Zugriff auf solche statischen Daten kann in executables und muss in relocatables über die Global Offset Table (GOT) stattfinden. Angenommen ein Programm läge an der physikalischen Adresse 0x0 und seine zugehörige GOT an der Adresse 0x1000 und am Offset 8 der GOT stünde die Adresse für das Symbol stringA, dann würde mit folgenden Assembly befehlen auf diesen Eintrag zugegriffen werden.

```
    auipc   t2, 0x1    # R_RISCV_GOT_HI20 (symbol), R_RISCV_RELAX
    lw      t2, 8(t2)  # R_RISCV_PCREL_LO12_I (auipc), R_RISCV_RELAX
```

In einer executable können die Immediates für diese Befehlssequenz direkt befüllt werden, da der Abstand des Programms zur GOT schon beim Kompilieren des Programms bekannt ist. Bei einem relocatable Programm belässt der Compiler diese Immediates mit 0 und markiert die Befehle in der „Relocation Section“ als unaufgelöst. Sowohl die GOT als auch die .data oder .rodata Sektionen können vom Betriebssystem beim Laden des Programms an beliebige Stellen im Speicher platziert werden. Sind alle Sektionen platziert, kann der Dynamische Linker anhand der Tags der Einträge in der Relocation Section herausfinden, wie er die Immediates für die aufzulösenden Symbole zu berechnen hat. `R_RISCV_GOT_HI20` z.B. bedeutet, dass für diese Instruktion die obersten 20 Bits der Differenz aus Position der Instruktion und Position der GOT benötigt. Die Relax Tags sollen anzeigen, dass es je nach Positionierung möglich sein könnte, eine der beiden Instruktionen zu sparen falls z.B. Instruktion und GOT nah genug beieinander liegen.

## Code

Bla bla bla Procedure Linkage Table

```
#PROCEDURE LINKAGE TABLE#
00000080 <.plt>:
.plt
.pltR:  auipc   t2, %pcrel_hi(.got.plt)
        sub     t1, t1, t3              # t1 = difference between caller and .pltR + 12
        lw      t3, %pcrel_lo(.pltR)(t2)  # t3 = addr(_dl_runtime_resolve)
        addi    t1, t1, -44             # subtract size of .pltR (32) and jalr offset in caller (12)
        addi    t0, t2, %pcrel_lo(.pltR)  # t0 = start of .got
        srli    t1, t1, 2               # index of .plt entry in .got.plt
        lw      t0, 4(t0)               # link map
        jr      t3

.plt0:  auipc   t3, %pcrel_hi(functionA@.got.plt)
        lw      t3, %pcrel_lo(.plt0)(t3)
        jalr    t1, t3
        nop
.plt1:  auipc   t3, %pcrel_hi(functionB@.got.plt)
        lw      t3, %pcrel_lo(.plt1)(t3)
        jalr    t1, t3
        nop
.plt2:  ...

#GLOBAL OFFSET TABLE#
000010ac <.got.plt>:
.got.plt
         .word 0xffffffff  #to be filled with address of the dynamic resolver
         .word 0x00000000  #to be filled with pointer to “link map”
         .word 0x00000080  #func entry 0
         .word 0x00000080  #func entry 1
         .word 0x00000080  #func entry 2
         ...
```