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

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
1 1 1 0 1 1	1	zero	rs1	0 0 0	rd	1 1 1 0 0 1 1	LW.X	R
1 1 1 1 0 1	1	rs2	rs1	0 0 0	zero	1 1 1 0 0 1 1	SW.X	R

Misc:

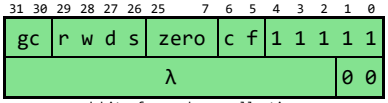
reg	alias	reg	alias
x0	zero	x16	a6
x1	ra	x17	a7
x2	sp	x18	s2
x3	gp (got)	x19	s3
x4	tp	x20	s4
x5	t0	x21	s5
x6	t1	x22	s6
x7	t2	x23	s7
x8	s0	x24	s8
x9	s1	x25	s9
x10	a0	x26	s10
x11	a1	x27	s11
x12	a2	x28	t3
x13	a3	x29	t4
x14	a4	x30	t5
x15	a5	x31	t6

csr-name	returns
MALC	alc_addr as pointer
MPAC	primitive alc_addr as pointer+index

Code	Exception
16	IndexOutOfBoundsException
17	IncompatibleTypeException
18	HeapOverFlowException
19	StateException

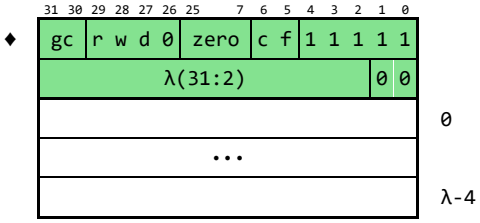
OBJECTS

Generic Header

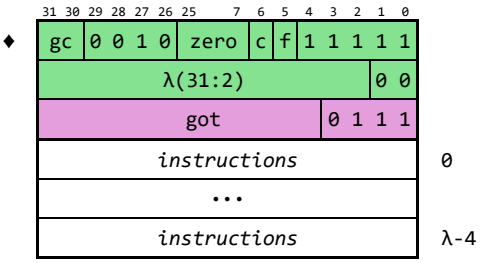


gc: reserved bits for garbage collection
r: readable
w: writable
d: data only (no pointers allowed)
s: sanctuary object for refugees
f: is stack frame object?
c: color of stack frame if f = 1, else don't care
λ: length of this object

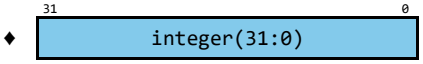
Ordinary



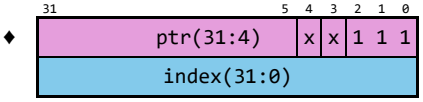
Executable



Refugee (Primitive)



Refugee (Pointer)

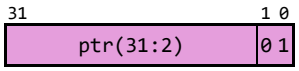


Invariant 1: data-only objects which are not readable and not writable are implicitly executable

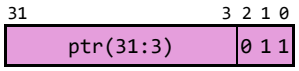
POINTERS & DATA

(inside objects)

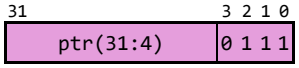
detour pointer (prim):



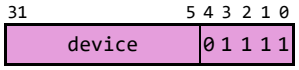
detour pointer (ptr):

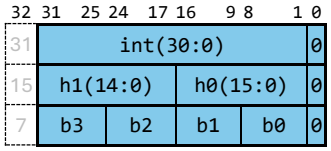


ordinary pointer:



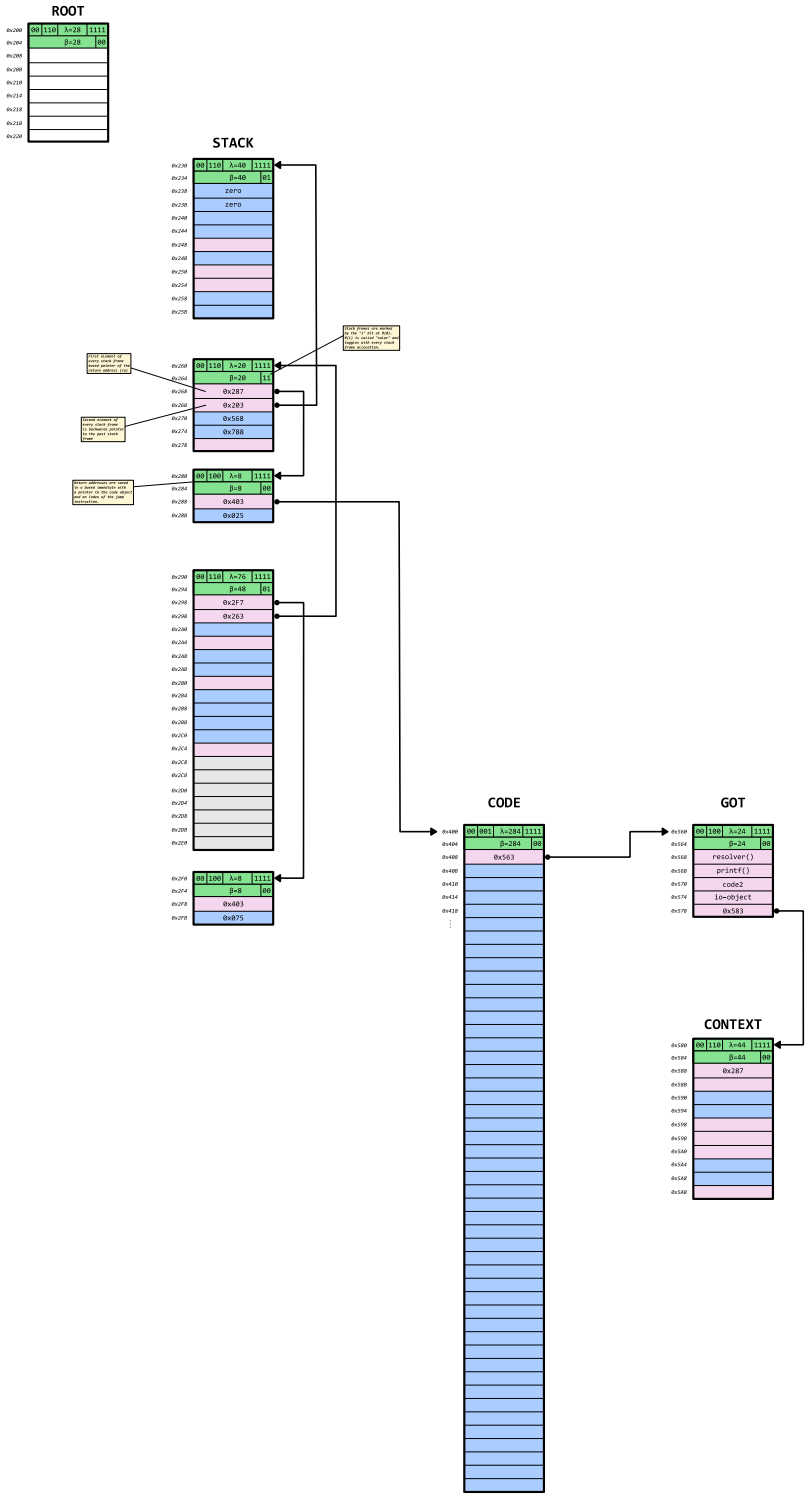
io pointer:





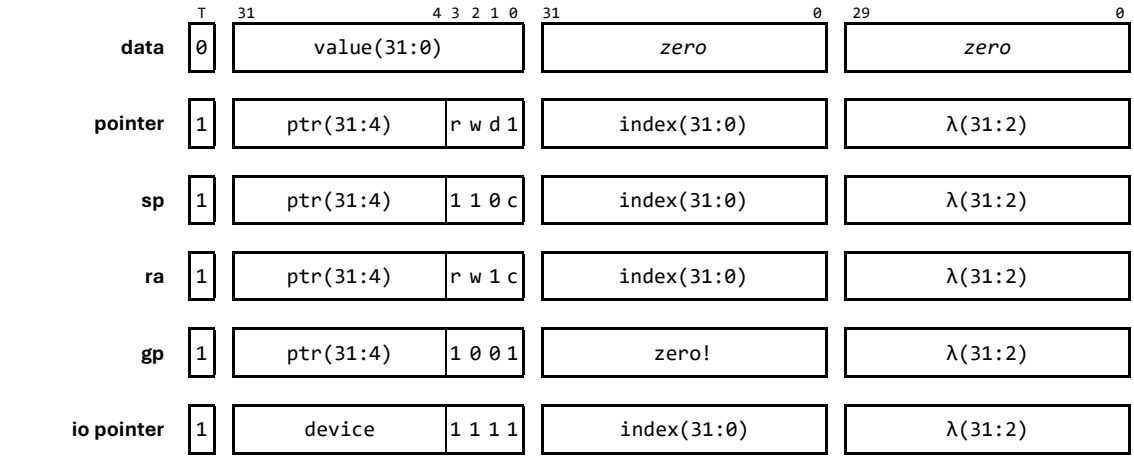
expel primitive if:

- 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
00 110 λ=28 1111
β=28 00
STACK
00 110 λ=40 1111
β=40 01
zero
zero
00 110 λ=20 1111
β=20 11
0x287
0x203
0x568
0x788
00 100 λ=8 1111
β=8 00
0x403
0x025
00 110 λ=76 1111
β=48 01
0x2F7
0x263
00 100 λ=8 1111
β=8 00
0x403
0x075
CODE
00 001 λ=284 1111
β=284 00
0x563
GOT
00 100 λ=24 1111
β=24 00
resolver()
printf()
code2
io-object
0x583
CONTEXT
00 110 λ=44 1111
β=44 00
0x287

REGISTER FILE & PIPELINE

Architectural Registers (x0-x31):



Flags/Tags:
r read access, **w** write access, **d** data only

Microarchitectural Registers:

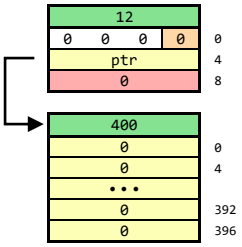
OBJECT INITIALIZATION

Deprecated yet again ;-;

CLEAR ON ALC

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

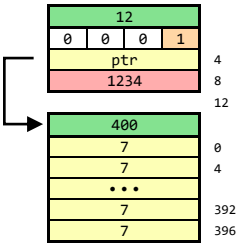
```
routine0:
  alci     s0, 12
.init0:
  clr      s0
  leb      t0, s0
  beq      zero,t0,.init0
  alci     t1, 400
.init1:
  clr      t1, zero
  leb      t0, t1
  beq      zero,t0,.init1
  sw       t1, 4(s0)
```



INIT WITH DEFAULTS

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

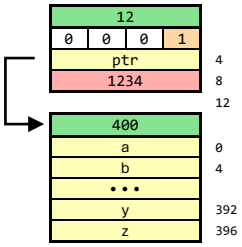
```
routine0:
  alci     s0, 12
  li       t1, 1
  sb       t1, 0(s0)
  alci     t2, 400
  sw       t2, 4(s0)
  li       t3, 1234
  sw       t3, 8(s0)

  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();
```

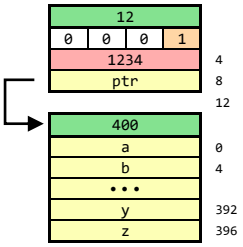
```
routine0:
  alci     s0, 12
  li       t1, 1
  sb       t1, 0(s0)
  li       t1, 1234
  sw       t1, 8(s0)
  ...
  jal      ra, routine1
  sw       a0, 4(s0)
```



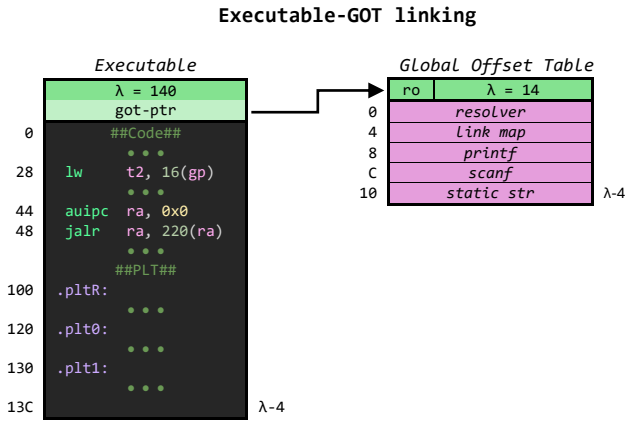
ALLOWED LAZY INIT

```
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	Notes
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	rd	rs1	---	●	imm	
sb/h/w	---	rs1	rs2	●	imm	
alc	rd	rs1	sp	●	---	*if rd = sp, also stores sp to index 4*
alci	rd	---	sp	●	imm	*if rd = sp, also stores sp to index 4*
alc.d	rd	rs1	---	-	---	*zero, ra, gp and sp forbidden for rd*
alci.d	rd	---	---	-	imm	*zero, ra, gp and sp forbidden for rd*
qsz	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)*
lw	*---*	*rs1*	*rs2*	*-*	*imm*	
A lw	rd	rs1	---	●	imm	*always*
a lw	rd	rs1	---	●	imm	*needed if rdata is immediate pointer*

Machine 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*
lw.x	rd	rs1	---	-	---	*load data from linear memory*
sw.x	rd	rs1	rs2	-	---	*store data to linear memory*

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
         ...
```