|  |  |  |  |
| --- | --- | --- | --- |
| **序号** | **机器码** | **汇编** | **说明** |
| 0 | 00100093 | addi x1, x0, 1 | 初始化常数 1 |
| 1 | 00200113 | addi x2, x0, 2 | 初始化常数 2 |
| 2 | 00300193 | addi x3, x0, 3 | 初始化常数 3 |
| 3 | 00400213 | addi x4, x0, 4 | 初始化常数 4 |
| 4 | 00500293 | addi x5, x0, 5 | 初始化常数 5 |
| 5 | 00000313 | addi x6, x0, 0 | 数据段基址 0 |
| 6 | 06400393 | addi x7, x0, 100 | 要写入内存的 100 |
| 7 | 00732023 | sw x7, 0(x6) | Store → Load 旁路准备 |
| 8 | 00208433 | add x8, x1, x2 | x8 = 1 + 2 = 3 |
| 9 | 003404B3 | add x9, x8, x3 | **RAW**：立即读取 x8 |
| 10 | 00032503 | lw x10, 0(x6) | 读取 100 → x10 |
| 11 | 004505B3 | add x11, x10, x4 | **Load‑Use**：用 x10 |
| 12 | 00940263 | beq x8, x9, +8 | 分支不跳（3 ≠ 6） |
| 13 | 00100613 | addi x12, x0, 1 | 错误路径指令 |
| 14 | 00840263 | beq x8, x8, +8 | 始终跳转（分支冒险） |
| 15 | 00100693 | addi x13, x0, 1 | 应被冲刷 |
| 16 | 00070713 | addi x14, x14, 0 | 伪 NOP |
| 17 | 00108093 | addi x1, x1, 1 | x1 再次写入（测试旁路） |
| 18 | 03200793 | addi x15, x0, 50 | 准备写入 50 |
| 19 | 00F32223 | sw x15, 4(x6) | 另一组 Store‑Load |
| 20 | 00432803 | lw x16, 4(x6) | 读取 50 → x16 |
| 21 | 005808B3 | add x17, x16, x5 | **Load‑Use** again |
| 22 | 01188933 | add x18, x17, x17 | **RAW**：立即用 x17 |
| 23 | FF288DE3 | beq x17, x18, -12 | 向后跳（不相等） |
| 24 | 00200993 | addi x19, x0, 2 | 错误路径指令 |
| 25 | FF188EE3 | beq x17, x17, -8 | 向后跳回（恒等） |
| 26 | 00300A13 | addi x20, x0, 3 | 冲刷目标 |
| 27 | 005A8A93 | addi x21, x21, 5 | 修改 x21 |
| 28 | 000B0B13 | addi x22, x22, 0 | NOP |
| 29 | 000B8B93 | addi x23, x23, 0 | NOP |

程序在执行到第 25 条指令后进入一个自循环（23 ↔ 25），因此寄存器值在第一次循环后即稳定；表中的数值即为该稳定状态。

|  |  |  |
| --- | --- | --- |
| **寄存器** | **预期值 (十进制)** | **产生路径** |
| x0 | 0 | 常数 0 |
| x1 | **2** | 1 → addi x1,1 再加 1 (addi x1,x1,1) |
| x2 | 2 | 初值 |
| x3 | 3 | 初值 |
| x4 | 4 | 初值 |
| x5 | 5 | 初值 |
| x6 | 0 | 数据段基址 |
| x7 | 100 | 常数写入后保持 |
| x8 | 3 | 1 + 2 |
| x9 | 6 | 3 + 3 |
| x10 | 100 | 从 D‑MEM 读回 |
| x11 | 104 | 100 + 4 |
| x12 | 1 | 位于未被冲刷的错误路径 |
| x13 | 0 | 指令 15 被冲刷，保持 0 |
| x14 | 0 | addi x14,+0 结果仍为 0 |
| x15 | 50 | 常数 50 |
| x16 | 50 | 从 D‑MEM 读回 |
| x17 | 55 | 50 + 5 |
| x18 | 110 | 55 + 55 |
| x19 | 2 | 循环体每次重写为 2 |
| x20 | 0 | 指令 26 被冲刷 |
| x21 | 0 | 指令 27 被冲刷 |
| x22 | 0 | NOP |
| x23 | 0 | NOP |
| x24‑x31 | 0 | 未被写入 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **地址** | **汇编** | **机器码** | **r1数据流(延后4条写回)** |  |
| 0 | LUI r1,1 | 000010B7 | xxxx | R1=4096 |
| 1 | ADDI r1,r1,-1 | FFF08093 | xxxx | R1=4095 |
| 2 | ADD r1,r1,r1 | 001080B3 | xxxx | R1=8190 |
| 3 | SUB r1,r1,r1 | 401080B3 | xxxx | R1=0 |
| 4 | ADDI r2,r1,7 | 00708113 | 4096 | R2=7 |
| 5 | ADDI r3,r1,15 | 00F08193 | 4095 | R3=15 |
| 6 | AND r1,r2,r3 | 003170B3 | 8190 | R1=7 |
| 7 | ANDI r1,r1,3 | 0030F093 | 0 | R1=3 |
|  |  |  |  |  |
|  |  |  |  |  |
| A | XOR r1,r1,r1 | 0010C0B3 | 0 | R1=0 |
| B | XORI r1,r1,100 | 0640C093 | 0 | R1=100 |
| C | SRLI r1,r1,6 | 0060D093 | 7 | R1=1 |
| D | SRL r1,r1,r1 | 0010D0B3 | 3 | R1=0 |
| E | ADDI r1,r1,4 | 00408093 | 0 | R1=4 |
| F | SLL r1,r1,r1 | 001090B3 | 100 | R1=64 |
| 10 | SLLI r1,r1,3 | 00309093 | 1 | R1=512 |
| \*\*\*\*11 | SRAI r1,r1,10 | 40A0D093 | 0 | R1=0 |
| 12 | ADDI r1,r1,-8 | FF808093 | 4 | R1=-8 |
| 13 | SRAI r1,r1,2 | 4020D093 | 64 | R1=-2 |
| 14 | SB r1,1(r2) | 001100A3 | 512 | b[8]=-2 |
| 15 | LBU r1,1(r2) | 00114083 | 0 | R1=254 |
| 16 | LB r1,1(r2) | 00110083 | -8 | R1=-2 |
| 17 | SH r1,-3(r3) | FE119EA3 | -2 | h[12]=-2 |
| 停顿18 | LHU r1,-3(r3) | FFD1D083 | -2 | R1=65534 |
| //19 | LH r1,-3(r3) | FFD19083 | 254 | R1=-2 |
| 1A | SW r1,0(r2) | 00112023 | -2 | w[7]=-2 |
| 1B | XOR r1,r1,r1 | 0010C0B3 | -2 | R1=0 |
| 1C | LW r1,0(r2) | 00012083 | 65534 | R1=-2 |
| 1D | XOR r2,r2,r2 | 00214133 | -2 | R2=0 |
| 1E | SLT r1,r2,r1 | 001120B3 | -2 | R1=0 |
| 1F | ADDI r2,r2,-1 | FFF10113 | 0 | R2=-1 |
| 20 | SLTU r1,r1,r2 | 0020B0B3 | -2 | R1=1 |
| 21 | SLTI r1,r2,-10 | FF612093 | -2 | R1=0 |
| 22 | SLTIU r1,r2,-10 | FF613093 | 0 | R1=0 |
| \*PC\*23 | AUIPC r1,1 | 00001097 | 0 | R1=4228 |
| 24 | XOR r1,r1,r1 | 0010C0B3 | 1 | R1=0 |
| 25 | XOR r3,r3,r3 | 0031C1B3 | 0 | R3=0 |
| 26 | ADDI r2,r2,3 | 00310113 | 0 | R2=2 |
| ON:ADD r1,r1,r2 | 002080B3 | 4236/2 | R1=2  R1=3 |  |
| 28 | ADDI r2,r2,-1 | FFF10113 | 0/2 | R2=1  R2=0 |
| 29 | BNE r2,r3,ON | FE311CE3 | 0/2 | J,notj |
| 2A | LUI r2,0 | 00000137 | 0/2 | R2=0 |
| 2B | ADDI r2,r2,2 | 00210113 | 3 | R2=2 |
| 2C | LUI r5,0 | 000002B7 | 3 | R5=0 |
| 2D | ADDI r5,r5,12 | 00C28293 | 3 | R5=12 |
| 2E | LUI r4,0 | 00000237 | 3 | R4=0 |
| 2F | ADDI r4,r4,1 | 00120213 | 3 | R4=1 |
| 30 | JAL r3,FACT | 03C001EF | 3 | R3=196 |
| 31 | LUI r2,0 | 00000137 | xxxx |  |
| 32 | LUI r3,0 | 000001B7 | xxxx |  |
| 33 | ADDI r3,r3,-1 | FFF18193 | xxxx |  |
| 34 | BLT r2,r3,L1 | 00314463 | xxxx |  |
| 35 | LUI r1,0 | 000000B7 | xxxx |  |
| L1:36 | L1:BGEU r2,r3,L2 | 00317463 | xxxx |  |
| 37 | ADDI r1,r1,1 | 00108093 | xxxx |  |
| L2:38 | L2:BGE r2,r3,L3 | 00315463 | xxxx |  |
| 39 | NOP | 00000013 | xxxx |  |
| L3:3A | L3:ADDI r1,r1,1 | 00108093 | xxxx |  |
| WAIT:3B | WAIT:BEQ r1,r1,WAIT | 00108063 | xxxx |  |
| 3C | NOP | 00000013 | xxxx |  |
| 3D | NOP | 00000013 | xxxx |  |
| 3E | NOP | 00000013 | xxxx |  |
| FACT:3F | FACT: LUI r1,0 | 000000B7 | 3/0/0 | R1=0,r1=0=r1 |
| 40 | BLTU r2,r4,RET | 02416863 | 3/0/0 | Notj,notj,j |
| 41 | SW r3,0(r5) | 0032A023 | 3/0 | w[12]=196,w[4]=284, |
| 42 | ADDI r5,r5,-4 | FFC28293 | 3/0 | R5=8,r5=0 |
| 43 | SW r2,0(r5) | 0022A023 | 0/0 | w[8]=2,[0]=1 |
| 44 | ADDI r5,r5,-4 | FFC28293 | 0/0 | R5=4,r5=-4 |
| 45 | ADDI r2,r2,-1 | FFF10113 | 0/0 | R2=1,r2=0 |
| 46 | JAL r3,FACT | FE5FF1EF | 0/0 | R3=284,r3=284 |
| 47 | ADDI r5,r5,-4 | FFC28293 |  |  |
| 48 | LW r2,0(r5) | 0002A103 | xxxx |  |
| 49 | ADD r1,r1,r2 | 002080B3 | xxxx |  |
| 4A | ADDI r5,r5,-4 | FFC28293 | xxxx |  |
| 4B | LW r3,0(r5) | 0002A183 | xxxx |  |
| 4C | RET: JALR r6,0(r3) | 00018367 | xxxx |  |
| 4D | NOP | 00000013 | xxxx |  |
| 4E | NOP | 00000013 | xxxx |  |
| 4F | NOP | 00000013 | xxxx |  |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Xxxx | | | | |
| xxxx | | | | |
| xxxx | | | | |
| xxxx | | | | |
| 4096 | | | | |
| 4095 | | | | |
| 8190 | | | | |
| 0 | | | | |
| 0 | | | | |
| 0 | | | | |
| 7 | | | | |
| 3 | | | | |
| 15 | | | | |
| 31 | | | | |
| 0 | | | | |
| 100 | | | | |
| 1 | | | | |
| 0 | | | | |
| 4 | | | | |
| 64 | | | | |
| 512 | | | | |
| 0 | | | | |
| -8 | | | | |
| -2 | | | | |
| -2 | | | | |
| 254 | | | | |
| -2 | | | | |
| -2 | | | | |
| 65534 | | | | |
| -2 | | | | |
| -2 | | | | |
| 0 | | | | |
| -2 | | | | |
| -2 | | | | |
| 0 | | | | |
| 0 | | | | |
| 1 | | | | |
| 0 | | | | |
| 4236 | | | | |
| 0 | | | | |
| 0 | | | | |
| 0  2  2  2  2 | | | | |
| 3 | | | | |
| 3 | | | | |
| 3 | | | | |
| 3 | | | | |
| 3 | | | | |
| 3 | | | | |
| 8 | | OR r1,r2,r3 | 003160B3 | 0 | R1=15 | |
| 9 | | ORI r1,r1,16 | 0100E093 | 0 | R1=31 | |

| **PC (dec)** | **Machine Code (hex)** | **Basic Code (简写)** | **Original Code** |
| --- | --- | --- | --- |
| **0** | **00100093** | **addi x1 x0 1** | **addi x1, x0, 1** |
| **1** | **00500113** | **addi x2 x0 5** | **addi x2, x0, 5** |
| **2** | **00208863** | **beq x1 x2 16** | **beq x1, x2, L1** |
| **3** | **00208093** | **addi x1 x1 2** | **addi x1, x1, 2** |
| **4** | **0020D463** | **bge x1 x2 8** | **bge x1, x2, L1** |
| **5** | **00308093** | **addi x1 x1 3** | **addi x1, x1, 3** |
| **6** | **0020D463** | **bge x1 x2 8** | **L1: bge x1, x2, L2** |
| **7** | **00408093** | **addi x1 x1 4** | **addi x1, x1, 4** |
| **8** | **00508093** | **addi x1 x1 5** | **L2: addi x1, x1, 5** |
| **9** | **0020F463** | **bgeu x1 x2 8** | **bgeu x1, x2, L3** |
| **10** | **00808093** | **addi x1 x1 8** | **addi x1, x1, 8** |
| **11** | **FF908093** | **addi x1 x1 -7** | **L3: addi x1, x1, -7** |
| **12** | **FE20C4E3** | **blt x1 x2 -24** | **L4: blt x1, x2, L1** |
| **13** | **00108093** | **addi x1 x1 1** | **addi x1, x1, 1** |
| **14** | **FF9FF06F** | **jal x0 -8** | **jal x0, L4** |