计算机组成原理实验报告

一、CPU 设计方案综述

总体设计综述

本 **CPU** 为 **Verilog** 实现的流水线 **CPU**，支持指令集包含

```
lb,lbu,lh,lhu,lw,sb,sh,sw,add,addu,sub,subu,mult,multu,div,divu,sll,srl,sra,,sllv,
srlv,srav,and,or,xor,nor,addi,addiu,andi,ori,xori,lui,slt,slti,sltiu,sltu,beq,bne,
blez,bgtz,bltz,bgez,j,jal,jalr,jr,mfhi,mflo,mthi,mtlo
```

为了实现这些功能，**CPU** 主要包含了 `ALU,Comp,Ctrl,Datapath,DM,Ext,GRF,Hazard,IFU,IM,LoadData,MDU,PC` ，这些模块并分成 5 级

关键模块定义

IFU

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	同步复位信号
`stall`	I	暂停信号
`Branch`	I	分支信号
`Jump`	I	跳转信号
`PCBranch[31:0]`	I	分支地址
`PCJump[31:0]`	I	跳转地址
`Instr[31:0]`	O	输出指令
`Pc[31:0]`	O	输出地址

序号	功能名称	功能描述
1	取指令	根据 `PC` 地址将指令读出
2	复位	当复位信号有效时，将 `PC` 设置为 `0x00003000`
3	暂停	将 `PC` 暂停，输出指令不变
4	计算下一个 `PC`	若 `Jump` 有效，则 `PC = JumpAddr` 若 `Branch` 有效，则 `PC = BranchAddr` 否则，`PC = PC + 4`

IM

信号名	方向	信号描述
`PC[31:0]`	I	当前 `PC` 地址
`Instr[31:0]`	O	对应地址的指令

PC

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	同步复位信号
`stall`	I	暂停信号
`NPC_Sel`	I	控制下一个 `PC` 信号
`NPC[31:0]`	I	`Branch` 或 `Jump` 的 `PC` 信号
`PC[31:0]`	O	计算后的 `PC`

ALU

信号名	方向	信号描述
`AluCtrl[3:0]`	I	控制运算方式信号
`A[31:0]`	I	第一运算数
`B[31:0]`	I	第二运算数
`S[4:0]`	I	移位数
`D[31:0]`	O	运算结果数

序号	功能名称	功能描述
1	算术运算	将 `A` 和 `B` 进行算术运算
2	按位逻辑运算	将 `A` 和 `B` 按位进行逻辑运算
3	移位运算	将 `B` 按照 `S` 的移位数进行移位

MDU

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	复位信号
`start`	I	乘除指令信号
`MDU_OP[3:0]`	I	`MDU` 操作信号
`A[31:0]`	I	第一运算数
`B[31:0]`	I	第二运算数
`Busy`	O	繁忙信号
`Hi[31:0]`	O	`HI` 寄存器值
`LO[31:0]`	O	`LO` 寄存器值

序号	功能名称	功能描述
1	复位	当复位信号有效时，将 `HI` 和 `LO` 清零
2	乘除	若进行乘法运算，高 32 位存入 `HI` 寄存器，低 32 位存入 `LO` 寄存器 若进行除法运算，$A \mod B$ 存入 `HI` 寄存器，$A \div B$ 存入 `LO` 寄存器
3	取数	读取指定寄存器
4	存数	将 A 写入指定寄存器

Ctrl

信号名	方向	信号描述
`Instr[31:0]`	I	当前指令
`RegDst[1:0]`	O	选择 `rd` 、 `rt` 或 `$31` 作为写入目标寄存器
`Ext_Op[1:0]`	O	控制扩展方式
`Branch[2:0]`	O	检测条件偏移指令
`AluCtrl[3:0]`	O	ALU 运算方式
`MDU_OP[3:0]`	O	MDU 运算方式
`AluSrc`	O	控制参与运算的数值
`RegWrite`	O	寄存器堆写入使能
`MemToReg`	O	控制 `DM` 数据写入寄存器堆
`MemWrite`	O	`DM` 写入使能
`Jump`	O	检测 `J` 指令信号
`Link`	O	将 `PC + 4` 写入寄存器信号
`Return`	O	将寄存器的地址写入 `PC` 信号
`start`	O	乘除指令信号
`ifmfhi`	O	`mfhi` 信号
`ifmflo`	O	`mflo` 信号
`ifmdu`	O	乘除槽信号
`Zero`	O	比较 0 信号
`Tuse_rs[2:0]`	O	使用 `rs` 的最大级数
`Tuse_rt[2:0]`	O	使用 `rt` 的最大级数
`Tnew[2:0]`	O	最新数据产生的级数
`LoadType[2:0]`	O	控制 `Load` 指令输出数据信号
`MuxData[2:0]`	O	E 级数据控制转发数据信号

Instr	RegDst	Ext_Op	Branch	AluCtrl	MDU_OP	AluSrc	RegWrite	MemToReg	MemWrite	Jump	Link	Return	start	ifmfhi	ifmflo	ifmdu	Zero	Tuse_rs	Tuse_rt	Tnew	LoadTy
add	rd	x	x	add	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
addu	rd	x	x	add	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
and	rd	x	x	and	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
sub	rd	x	x	sub	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
subu	rd	x	x	sub	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
jr	x	x	x	x	x	0	0	0	0	1	0	1	0	0	0	0	0	D	x	x	x
jalr	rd	x	x	x	x	0	1	0	0	1	1	1	0	0	0	0	0	D	x	F	x
or	rd	x	x	or	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
xor	rd	x	x	xor	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
nor	rd	x	x	nor	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
sll	rd	x	x	sll	x	0	1	0	0	0	0	0	0	0	0	0	0	x	E	E	x
srl	rd	x	x	srl	x	0	1	0	0	0	0	0	0	0	0	0	0	x	E	E	x
sra	rd	x	x	sra	x	0	1	0	0	0	0	0	0	0	0	0	0	x	E	E	x
slt	rd	x	x	slt	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
sltu	rd	x	x	sltu	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
sllv	rd	x	x	sllv	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
srlv	rd	x	x	srlv	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
srav	rd	x	x	srav	x	0	1	0	0	0	0	0	0	0	0	0	0	E	E	E	x
mult	x	x	x	x	mult	0	0	0	0	0	0	0	1	0	0	1	0	E	E	x	x
multu	x	x	x	x	multu	0	0	0	0	0	0	0	1	0	0	1	0	E	E	x	x
div	x	x	x	x	div	0	0	0	0	0	0	0	1	0	0	1	0	E	E	x	x
divu	x	x	x	x	divu	0	0	0	0	0	0	0	1	0	0	1	0	E	E	x	x
mthi	x	x	x	x	mthi	0	0	0	0	0	0	0	0	0	0	1	0	E	x	x	x
mtlo	x	x	x	x	mtlo	0	0	0	0	0	0	0	0	0	0	1	0	E	x	x	x
mfhi	rd	x	x	x	x	0	1	0	0	0	0	0	0	1	0	1	0	x	x	E	x
mflo	rd	x	x	x	x	0	1	0	0	0	0	0	0	0	1	1	0	x	x	E	x
addi	rt	sign	x	add	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
addiu	rt	sign	x	add	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
andi	rt	zero	x	and	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
ori	rt	zero	x	or	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
xori	rt	zero	x	xor	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
lw	rt	sign	x	add	x	1	1	1	0	0	0	0	0	0	0	0	0	E	x	M	word
lb	rt	sign	x	add	x	1	1	1	0	0	0	0	0	0	0	0	0	E	x	M	sign_by
lbu	rt	sign	x	add	x	1	1	1	0	0	0	0	0	0	0	0	0	E	x	M	byte
lh	rt	sign	x	add	x	1	1	1	0	0	0	0	0	0	0	0	0	E	x	M	sign_ha
lhu	rt	sign	x	add	x	1	1	1	0	0	0	0	0	0	0	0	0	E	x	M	half
lui	rt	upper	x	add	x	1	1	0	0	0	0	0	0	0	0	0	0	x	x	D	x
sw	x	sign	x	add	x	1	0	0	1	0	0	0	0	0	0	0	0	E	M	x	x
sb	x	sign	x	add	x	1	0	0	1	0	0	0	0	0	0	0	0	E	M	x	x
sh	x	sign	x	add	x	1	0	0	1	0	0	0	0	0	0	0	0	E	M	x	x
j	x	x	x	x	x	0	0	0	0	1	0	0	0	0	0	0	0	x	x	x	x
jal	$31	x	x	x	x	0	1	0	0	1	1	0	0	0	0	0	0	x	x	F	x
beq	x	sign	010	x	x	0	0	0	0	0	0	0	0	0	0	0	0	D	D	x	x
bne	x	sign	101	x	x	0	0	0	0	0	0	0	0	0	0	0	0	D	D	x	x
slti	rt	sign	x	slt	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
sltiu	rt	sign	x	sltu	x	1	1	0	0	0	0	0	0	0	0	0	0	E	x	E	x
bgez	x	sign	110	x	x	0	0	0	0	0	0	0	0	0	0	0	1	D	x	x	x
bgtz	x	sign	100	x	x	0	0	0	0	0	0	0	0	0	0	0	1	D	x	x	x
blez	x	sign	011	x	x	0	0	0	0	0	0	0	0	0	0	0	1	D	x	x	x
bltz	x	sign	001	x	x	0	0	0	0	0	0	0	0	0	0	0	1	D	x	x	x

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	同步复位信号
`stall_PC`	I	`PC` 暂停信号
`stall_FD`	I	`FD` 寄存器暂停信号
`stall_DE`	I	`DE` 寄存器暂停信号
`stall_EM`	I	`EM` 寄存器暂停信号
`stall_MW`	I	`MW` 寄存器暂停信号
`clr_FD`	I	`FD` 寄存器清空信号
`clr_DE`	I	`DE` 寄存器清空信号
`clr_EM`	I	`EM` 寄存器清空信号
`clr_MW`	I	`MW` 寄存器清空信号
`ForwardSel_D1[4:0]`	I	D 级 `RD1` 转发信号
`ForwardSel_D2[4:0]`	I	D 级 `RD2` 转发信号
`ForwardSel_EA[4:0]`	I	E 级 `A` 转发信号
`ForwardSel_EB[4:0]`	I	E 级 `B` 转发信号
`ForwardSel_MD[4:0]`	I	M 级写入数据转发信号
`Branch_D[2:0]`	I	D 级 `Branch` 判断信号
`ExtCtrl_D[1:0]`	I	D 级扩展控制信号
`RegDst[1:0]`	I	D 级 `A3` 控制信号
`Jump_D`	I	D 级跳转信号
`Return_D`	I	D 级跳转寄存器信号
`RegWrite_D`	I	D 级写入使能信号
`AluCtrl_E[3:0]`	I	E 级 `ALU` 控制运算信号
`MDU_OP_E[3:0]`	I	E 级乘除槽控制运算信号
`AluSrc_E`	I	E 级控制运算数据信号
`ifmfhi_E`	I	E 级 `mfhi` 信号
`ifmflo_E`	I	E 级 `mflo` 信号
`start_E`	I	E 级乘除信号
`MemWrite_M`	I	M 级 `DM` 写入使能信号
`StoreType_M[1:0]`	I	M 级控制写入数据类型信号
`MuxData_M[2:0]`	I	M 级控制转发数据信号
`MemToReg_W`	I	W 级控制写入 `DM` 数据信号
`Link_W`	I	W 级写入 `PC + 8` 信号
`RegWrite_W`	I	W 级 `GRF` 写入使能信号
`ifmfhi_W`	I	W 级 `mfhi` 信号
`ifmflo_W`	I	W 级 `mflo` 信号
`Instr_D[31:0]`	O	D 级指令
`Instr_E[31:0]`	O	E 级指令
`Instr_M[31:0]`	O	M 级指令
`Instr_W[31:0]`	O	W 级指令
`PCplus4_D[31:0]`	O	D 级 `PCplus4` 信号
`PCplus4_E[31:0]`	O	E 级 `PCplus4` 信号
`PCplus4_M[31:0]`	O	M 级 `PCplus4` 信号
`PCplus4_W[31:0]`	O	W 级 `PCplus4` 信号

信号名	方向	信号描述
`PCplus8_D[31:0]`	O	D 级 `PCplus` 8 信号
`PCplus8_E[31:0]`	O	E 级 `PCplus` 8 信号
`PCplus8_M[31:0]`	O	M 级 `PCplus` 8 信号
`PCplus8_W[31:0]`	O	W 级 `PCplus` 8 信号
`A3_E[4:0]`	O	E 级 `A3` 地址
`A3_M[4:0]`	O	M 级 `A3` 地址
`A3_W[4:0]`	O	W 级 `A3` 地址
`Busy_E`	O	E 级乘除槽繁忙信号

DM

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	同步复位信号
`MemWrite`	I	写入使能信号
`Addr[31:0]`	I	数据存储器地址
`WriteData[31:0]`	I	写入数据
`PC[31:0]`	I	当前 `PC` 地址
`StoreType[1:0]`	I	数据类型信号
`DMOut[31:0]`	O	对应输出数据

序号	功能名称	功能描述
1	复位	当 `reset` 信号有效则将 `DM` 数据清零
2	写数据	当 `MemWrite` 有效且时钟上升沿时，将 `WriteData` 数据写入指定地址
3	读数据	从 `Addr` 读出数据

LoadData

信号名	方向	信号描述
`LoadType[2:0]`	I	控制数据类型信号
`DataIn[31:0]`	I	原始数据
`Offset[1:0]`	I	偏移量
`DataOut[31:0]`	O	根据类型定义后的数据

序号	功能名称	功能描述
1	转换数据	将数据转换成应有的数据类型

Ext

信号名	方向	信号描述
`ExtCtrl[1:0]`	I	控制扩展方式信号
`imm16[15:0]`	I	16 位立即数
`imm[31:0]`	O	扩展后的立即数

序号	功能名称	功能描述
1	扩展	按照 `ExtCtrl` 信号指定扩展数据和方式

GRF

信号名	方向	信号描述
`clk`	I	时钟信号
`reset`	I	同步复位信号
`RegWrite`	I	写入使能信号
`A1[4:0]`	I	指定 32 个寄存器中的一个，输出其中数据到 `RD1`
`A2[4:0]`	I	指定 32 个寄存器中的一个，输出其中数据到 `RD2`
`A3[4:0]`	I	指定 32 个寄存器中的一个，写入 `WriteData` 数据
`WriteData[31:0]`	I	输入数据
`PC[31:0]`	I	`PC` 地址
`RD1[31:0]`	O	`A1` 指定寄存器中的数据
`RD2[31:0]`	O	`A2` 指定寄存器中的数据

序号	功能名称	功能描述
1	复位	当复位信号有效时，寄存器清零
2	写数据	读出 `A1,A2` 的寄存器数据到 `RD1,RD2`
3	读数据	当 `RegWrite` 有效时且时钟上升沿时，将 `WriteData` 写入指定寄存器内

Hazard

信号名	方向	信号描述
`Instr_D[31:0]`	I	D 级指令信号
`Tuse_rs_D[2:0]`	I	D 级 `rs` 使用数据信号
`Tuse_rt_D[2:0]`	I	D 级 `rt` 使用数据信号
`ifmdu_D`	I	D 级乘除槽指令
`Instr_E[31:0]`	I	E 级指令信号
`Tnew_E[2:0]`	I	E 级数据完成信号
`A3_E[4:0]`	I	E 级 `A3` 地址
`start_E`	I	E 级触发乘除槽信号
`Busy_E`	I	E 级乘除槽繁忙信号
`Instr_M[31:0]`	I	M 级指令信号
`Tnew_M[2:0]`	I	M 级数据完成信号
`A3_M[4:0]`	I	M 级 `A3` 地址
`Instr_W[31:0]`	I	W 级指令信号
`Tnew_W[2:0]`	I	W 级数据完成信号
`A3_W[4:0]`	I	W 级 `A3` 地址
`ForwardSel_D1[4:0]`	O	D 级 `RD1` 转发信号
`ForwardSel_D2[4:0]`	O	D 级 `RD2` 转发信号
`ForwardSel_EA[4:0]`	O	E 级 `A` 转发信号
`ForwardSel_EB[4:0]`	O	E 级 `B` 转发信号
`ForwardSel_MD[4:0]`	O	M 级 `DM` 写入数据转发信号
`stall_PC`	O	暂停 `PC` 信号
`stall_FD`	O	暂停 `FD` 寄存器信号
`stall_DE`	O	暂停 `DE` 寄存器信号
`stall_EM`	O	暂停 `EM` 寄存器信号
`stall_MW`	O	暂停 `MW` 寄存器信号
`clr_FD`	O	清除 `FD` 寄存器信号
`clr_DE`	O	清除 `DE` 寄存器信号
`clr_EM`	O	清除 `EM` 寄存器信号
`clr_MW`	O	清除 `MW` 寄存器信号

Forward

信号名	方向	信号描述
`ForwardSel_D1[4:0]`	I	D 级 `RD1` 转发信号
`ForwardSel_D2[4:0]`	I	D 级 `RD2` 转发信号
`ForwardSel_EA[4:0]`	I	E 级 `A` 转发信号
`ForwardSel_EB[4:0]`	I	E 级 `B` 转发信号
`ForwardSel_MD[4:0]`	I	M 级 `DM` 写入数据转发信号
`RD1_D[31:0]`	I	D 级 `RD1` 数据
`RD2_D[31:0]`	I	D 级 `RD2` 数据
`PCplus8_E[31:0]`	I	E 级 `PCplus8` 数据
`imm_E[31:0]`	I	E 级 `imm` 数据
`RD1_E[31:0]`	I	E 级 `RD1` 数据
`RD2_E[31:0]`	I	E 级 `RD2` 数据
`MuxData_M[2:0]`	I	M 级数据选择信号
`PCplus8_M[31:0]`	I	M 级 `PCplus8` 数据
`imm_M[31:0]`	I	M 级 `imm` 数据
`RD2_M[31:0]`	I	M 级 `RD2` 数据
`AluOut_M[31:0]`	I	M 级 `ALU` 数据
`HI_M[31:0]`	I	M 级 `HI` 数据
`LO_M[31:0]`	I	M 级 `LO` 数据
`MuxData_W[2:0]`	I	W 级数据选择信号
`PCplus8_W[31:0]`	I	W 级 `PCplus8` 数据
`imm_W[31:0]`	I	W 级 `imm` 数据
`AluOut_W[31:0]`	I	W 级 `ALU` 数据
`DMOut_W[31:0]`	I	W 级 `DM` 数据
`HI_W[31:0]`	I	W 级 `HI` 数据
`LO_W[31:0]`	I	W 级 `LO` 数据
`MF_RD1_D[31:0]`	O	D 级 `RD1` 转发数据
`MF_RD2_D[31:0]`	O	D 级 `RD1` 转发数据
`MF_A_E[31:0]`	O	E 级 `A` 转发数据
`MF_B_E[31:0]`	O	E 级 `B` 转发数据
`MF_RD2_M[31:0]`	O	M 级 `RD2` 转发数据

序号	功能名称	功能描述
1	转发	转发前几级的数据

Comp

信号名	方向	信号描述
`zero`	I	比较零信号
`A[31:0]`	I	`RD1` 信号
`B[31:0]`	I	`RD2` 信号
`Comp_Out[2:0]`	O	比较后输出信号

序号	功能名称	功能描述
1	数据比较	若 $A > B$ 则 `Comp_Out = 100` 若 $A = B$ 则 `Comp_Out = 010` 若 $A < B$ 则 `Comp_Out = 001`

重要机制实现方法

1. 跳转

   利用 `Branch` 和 `Jump` 来判断下一个时钟沿写入的 `PC` 值

2. 转发

   利用 $Tuse_{rs}$ 或 $Tuse_{rt} \geq$ 当前级数且 $Tnew \leq$ 当前级数，表示数据已经生成，可以直接转发

3. 暂停

   若 $Tuse_{rs} > Tnew$ ，则将处理器暂停，直到数据生成为止

二、测试方案

典型测试样例

汇编代码

```
lui $t0, 0x7fff
ori $t0, 0xffff
mult $t0, $t0
mfhi $t1
mflo $t2
div $t1, $t2
mfhi $t1
mflo $t2
mthi $t0
mtlo $t0
mfhi $t1
mflo $t2

lui $t0, 0xffff
ori $t0, 0xffff
multu $t0, $t0
mfhi $t1
mflo $t2
divu $t1, $t2
mfhi $t1
mflo $t2
mthi $t0
mtlo $t0
mfhi $t1
mflo $t2

addi $t1, $0, 27
subi $t0, $0, 12
multu $t0, $t1
divu $t1, $t0
mfhi $t2
mflo $t3
mult $t0, $t1
mfhi $t2
mflo $t3
div $t0, $t1
mfhi $t2
mflo $t3
```

机器码

```
3c087fff
3508ffff
01080018
00004810
00005012
012a001a
00004810
00005012
01000011
01000013
00004810
00005012
3c08ffff
3508ffff
01080019
00004810
00005012
012a001b
00004810
00005012
01000011
01000013
00004810
00005012
2009001b
2001000c
00014022
01090019
0128001b
00005010
00005812
01090018
00005010
00005812
0109001a
00005010
```

```
00005812
```

期望结果

```
@00003000: $ 8 <= 7fff0000
@00003004: $ 8 <= 7fffffff
@0000300c: $ 9 <= 3fffffff
@00003010: $10 <= 00000001
@00003018: $ 9 <= 00000000
@0000301c: $10 <= 3fffffff
@00003028: $ 9 <= 7fffffff
@0000302c: $10 <= 7fffffff
@00003030: $ 8 <= ffff0000
@00003034: $ 8 <= ffffffff
@0000303c: $ 9 <= fffffffe
@00003040: $10 <= 00000001
@00003048: $ 9 <= 00000000
@0000304c: $10 <= fffffffe
@00003058: $ 9 <= ffffffff
@0000305c: $10 <= ffffffff
@00003060: $ 9 <= 0000001b
@00003064: $ 1 <= 0000000c
@00003068: $ 8 <= fffffff4
@00003074: $10 <= 0000001b
@00003078: $11 <= 00000000
@00003080: $10 <= ffffffff
@00003084: $11 <= fffffebc
@0000308c: $10 <= fffffff4
@00003090: $11 <= 00000000
```

汇编代码

```
li $t0, 0
li $s0, 256
for:
    beq $t0, $s0, for_end
    nop
    add $t0, $0, $t0
    sb $t0, ($t0)
    add $t0, $0, $t0
    j for
    addi $t0, $t0, 1
for_end:
add $t0, $0, $0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
lb $a0, 0($t0)
lb $t1, 1($t0)
add $t0, $t1, $a0
```

机器码

```
24080000
24100100
11100006
00000000
00084020
a1080000
00084020
08000c02
21080001
00004020
81040000
81090001
01244020
81040000
81090001
01244020
81040000
81090001
01244020
81040000
81090001
01244020
81040000
81090001
01244020
81040000
81090001
01244020
```

期望结果

```
@00003000: $ 8 <= 00000000
@00003004: $16 <= 00000100
@00003010: $ 8 <= 00000000
@00003014: *00000000 <= 00000000
@00003018: $ 8 <= 00000000
@00003020: $ 8 <= 00000001
@00003010: $ 8 <= 00000001
@00003014: *00000000 <= 00000100
@00003018: $ 8 <= 00000001
@00003020: $ 8 <= 00000002
@00003010: $ 8 <= 00000002
@00003014: *00000000 <= 00020100
@00003018: $ 8 <= 00000002
@00003020: $ 8 <= 00000003
@00003010: $ 8 <= 00000003
@00003014: *00000000 <= 03020100
@00003018: $ 8 <= 00000003
```

```
@00003020: $ 8 <= 00000004
@00003010: $ 8 <= 00000004
@00003014: *00000004 <= 00000004
@00003018: $ 8 <= 00000004
@00003020: $ 8 <= 00000005
@00003010: $ 8 <= 00000005
@00003014: *00000004 <= 00000504
@00003018: $ 8 <= 00000005
@00003020: $ 8 <= 00000006
@00003010: $ 8 <= 00000006
@00003014: *00000004 <= 00060504
@00003018: $ 8 <= 00000006
@00003020: $ 8 <= 00000007
@00003010: $ 8 <= 00000007
@00003014: *00000004 <= 07060504
@00003018: $ 8 <= 00000007
@00003020: $ 8 <= 00000008
@00003010: $ 8 <= 00000008
@00003014: *00000008 <= 00000008
@00003018: $ 8 <= 00000008
@00003020: $ 8 <= 00000009
@00003010: $ 8 <= 00000009
@00003014: *00000008 <= 00000908
@00003018: $ 8 <= 00000009
@00003020: $ 8 <= 0000000a
@00003010: $ 8 <= 0000000a
@00003014: *00000008 <= 000a0908
@00003018: $ 8 <= 0000000a
@00003020: $ 8 <= 0000000b
@00003010: $ 8 <= 0000000b
@00003014: *00000008 <= 0b0a0908
@00003018: $ 8 <= 0000000b
@00003020: $ 8 <= 0000000c
@00003010: $ 8 <= 0000000c
@00003014: *0000000c <= 0000000c
@00003018: $ 8 <= 0000000c
@00003020: $ 8 <= 0000000d
@00003010: $ 8 <= 0000000d
@00003014: *0000000c <= 00000d0c
@00003018: $ 8 <= 0000000d
@00003020: $ 8 <= 0000000e
@00003010: $ 8 <= 0000000e
@00003014: *0000000c <= 000e0d0c
@00003018: $ 8 <= 0000000e
@00003020: $ 8 <= 0000000f
@00003010: $ 8 <= 0000000f
@00003014: *0000000c <= 0f0e0d0c
@00003018: $ 8 <= 0000000f
@00003020: $ 8 <= 00000010
@00003010: $ 8 <= 00000010
@00003014: *00000010 <= 00000010
@00003018: $ 8 <= 00000010
@00003020: $ 8 <= 00000011
@00003010: $ 8 <= 00000011
@00003014: *00000010 <= 00001110
@00003018: $ 8 <= 00000011
@00003020: $ 8 <= 00000012
@00003010: $ 8 <= 00000012
@00003014: *00000010 <= 00121110
@00003018: $ 8 <= 00000012
@00003020: $ 8 <= 00000013
@00003010: $ 8 <= 00000013
@00003014: *00000010 <= 13121110
@00003018: $ 8 <= 00000013
@00003020: $ 8 <= 00000014
@00003010: $ 8 <= 00000014
@00003014: *00000014 <= 00000014
@00003018: $ 8 <= 00000014
@00003020: $ 8 <= 00000015
@00003010: $ 8 <= 00000015
@00003014: *00000014 <= 00001514
@00003018: $ 8 <= 00000015
@00003020: $ 8 <= 00000016
@00003010: $ 8 <= 00000016
@00003014: *00000014 <= 00161514
@00003018: $ 8 <= 00000016
@00003020: $ 8 <= 00000017
@00003010: $ 8 <= 00000017
@00003014: *00000014 <= 17161514
@00003018: $ 8 <= 00000017
@00003020: $ 8 <= 00000018
@00003010: $ 8 <= 00000018
@00003014: *00000018 <= 00000018
@00003018: $ 8 <= 00000018
@00003020: $ 8 <= 00000019
```

```
@00003010: $ 8 <= 00000019
@00003014: *00000018 <= 00001918
@00003018: $ 8 <= 00000019
@00003020: $ 8 <= 0000001a
@00003010: $ 8 <= 0000001a
@00003014: *00000018 <= 001a1918
@00003018: $ 8 <= 0000001a
@00003020: $ 8 <= 0000001b
@00003010: $ 8 <= 0000001b
@00003014: *00000018 <= 1b1a1918
@00003018: $ 8 <= 0000001b
@00003020: $ 8 <= 0000001c
@00003010: $ 8 <= 0000001c
@00003014: *0000001c <= 0000001c
@00003018: $ 8 <= 0000001c
@00003020: $ 8 <= 0000001d
@00003010: $ 8 <= 0000001d
@00003014: *0000001c <= 00001d1c
@00003018: $ 8 <= 0000001d
@00003020: $ 8 <= 0000001e
@00003010: $ 8 <= 0000001e
@00003014: *0000001c <= 001e1d1c
@00003018: $ 8 <= 0000001e
@00003020: $ 8 <= 0000001f
@00003010: $ 8 <= 0000001f
@00003014: *0000001c <= 1f1e1d1c
@00003018: $ 8 <= 0000001f
@00003020: $ 8 <= 00000020
@00003010: $ 8 <= 00000020
@00003014: *00000020 <= 00000020
@00003018: $ 8 <= 00000020
@00003020: $ 8 <= 00000021
@00003010: $ 8 <= 00000021
@00003014: *00000020 <= 00002120
@00003018: $ 8 <= 00000021
@00003020: $ 8 <= 00000022
@00003010: $ 8 <= 00000022
@00003014: *00000020 <= 00222120
@00003018: $ 8 <= 00000022
@00003020: $ 8 <= 00000023
@00003010: $ 8 <= 00000023
@00003014: *00000020 <= 23222120
@00003018: $ 8 <= 00000023
@00003020: $ 8 <= 00000024
@00003010: $ 8 <= 00000024
@00003014: *00000024 <= 00000024
@00003018: $ 8 <= 00000024
@00003020: $ 8 <= 00000025
@00003010: $ 8 <= 00000025
@00003014: *00000024 <= 00002524
@00003018: $ 8 <= 00000025
@00003020: $ 8 <= 00000026
@00003010: $ 8 <= 00000026
@00003014: *00000024 <= 00262524
@00003018: $ 8 <= 00000026
@00003020: $ 8 <= 00000027
@00003010: $ 8 <= 00000027
@00003014: *00000024 <= 27262524
@00003018: $ 8 <= 00000027
@00003020: $ 8 <= 00000028
@00003010: $ 8 <= 00000028
@00003014: *00000028 <= 00000028
@00003018: $ 8 <= 00000028
@00003020: $ 8 <= 00000029
@00003010: $ 8 <= 00000029
@00003014: *00000028 <= 00002928
@00003018: $ 8 <= 00000029
@00003020: $ 8 <= 0000002a
@00003010: $ 8 <= 0000002a
@00003014: *00000028 <= 002a2928
@00003018: $ 8 <= 0000002a
@00003020: $ 8 <= 0000002b
@00003010: $ 8 <= 0000002b
@00003014: *00000028 <= 2b2a2928
@00003018: $ 8 <= 0000002b
@00003020: $ 8 <= 0000002c
@00003010: $ 8 <= 0000002c
@00003014: *0000002c <= 0000002c
@00003018: $ 8 <= 0000002c
@00003020: $ 8 <= 0000002d
@00003010: $ 8 <= 0000002d
@00003014: *0000002c <= 00002d2c
@00003018: $ 8 <= 0000002d
@00003020: $ 8 <= 0000002e
@00003010: $ 8 <= 0000002e
```

```
@00003014: *0000002c <= 002e2d2c
@00003018: $ 8 <= 0000002e
@00003020: $ 8 <= 0000002f
@00003010: $ 8 <= 0000002f
@00003014: *0000002c <= 2f2e2d2c
@00003018: $ 8 <= 0000002f
@00003020: $ 8 <= 00000030
@00003010: $ 8 <= 00000030
@00003014: *00000030 <= 00000030
@00003018: $ 8 <= 00000030
@00003020: $ 8 <= 00000031
@00003010: $ 8 <= 00000031
@00003014: *00000030 <= 00003130
@00003018: $ 8 <= 00000031
@00003020: $ 8 <= 00000032
@00003010: $ 8 <= 00000032
@00003014: *00000030 <= 00323130
@00003018: $ 8 <= 00000032
@00003020: $ 8 <= 00000033
@00003010: $ 8 <= 00000033
@00003014: *00000030 <= 33323130
@00003018: $ 8 <= 00000033
@00003020: $ 8 <= 00000034
@00003010: $ 8 <= 00000034
@00003014: *00000034 <= 00000034
@00003018: $ 8 <= 00000034
@00003020: $ 8 <= 00000035
@00003010: $ 8 <= 00000035
@00003014: *00000034 <= 00003534
@00003018: $ 8 <= 00000035
@00003020: $ 8 <= 00000036
@00003010: $ 8 <= 00000036
@00003014: *00000034 <= 00363534
@00003018: $ 8 <= 00000036
@00003020: $ 8 <= 00000037
@00003010: $ 8 <= 00000037
@00003014: *00000034 <= 37363534
@00003018: $ 8 <= 00000037
@00003020: $ 8 <= 00000038
@00003010: $ 8 <= 00000038
@00003014: *00000038 <= 00000038
@00003018: $ 8 <= 00000038
@00003020: $ 8 <= 00000039
@00003010: $ 8 <= 00000039
@00003014: *00000038 <= 00003938
@00003018: $ 8 <= 00000039
@00003020: $ 8 <= 0000003a
@00003010: $ 8 <= 0000003a
@00003014: *00000038 <= 003a3938
@00003018: $ 8 <= 0000003a
@00003020: $ 8 <= 0000003b
@00003010: $ 8 <= 0000003b
@00003014: *00000038 <= 3b3a3938
@00003018: $ 8 <= 0000003b
@00003020: $ 8 <= 0000003c
@00003010: $ 8 <= 0000003c
@00003014: *0000003c <= 0000003c
@00003018: $ 8 <= 0000003c
@00003020: $ 8 <= 0000003d
@00003010: $ 8 <= 0000003d
@00003014: *0000003c <= 00003d3c
@00003018: $ 8 <= 0000003d
@00003020: $ 8 <= 0000003e
@00003010: $ 8 <= 0000003e
@00003014: *0000003c <= 003e3d3c
@00003018: $ 8 <= 0000003e
@00003020: $ 8 <= 0000003f
@00003010: $ 8 <= 0000003f
@00003014: *0000003c <= 3f3e3d3c
@00003018: $ 8 <= 0000003f
@00003020: $ 8 <= 00000040
@00003010: $ 8 <= 00000040
@00003014: *00000040 <= 00000040
@00003018: $ 8 <= 00000040
@00003020: $ 8 <= 00000041
@00003010: $ 8 <= 00000041
@00003014: *00000040 <= 00004140
@00003018: $ 8 <= 00000041
@00003020: $ 8 <= 00000042
@00003010: $ 8 <= 00000042
@00003014: *00000040 <= 00424140
@00003018: $ 8 <= 00000042
@00003020: $ 8 <= 00000043
@00003010: $ 8 <= 00000043
@00003014: *00000040 <= 43424140
```

```
@00003018: $ 8 <= 00000043
@00003020: $ 8 <= 00000044
@00003010: $ 8 <= 00000044
@00003014: *00000044 <= 00000044
@00003018: $ 8 <= 00000044
@00003020: $ 8 <= 00000045
@00003010: $ 8 <= 00000045
@00003014: *00000044 <= 00004544
@00003018: $ 8 <= 00000045
@00003020: $ 8 <= 00000046
@00003010: $ 8 <= 00000046
@00003014: *00000044 <= 00464544
@00003018: $ 8 <= 00000046
@00003020: $ 8 <= 00000047
@00003010: $ 8 <= 00000047
@00003014: *00000044 <= 47464544
@00003018: $ 8 <= 00000047
@00003020: $ 8 <= 00000048
@00003010: $ 8 <= 00000048
@00003014: *00000048 <= 00000048
@00003018: $ 8 <= 00000048
@00003020: $ 8 <= 00000049
@00003010: $ 8 <= 00000049
@00003014: *00000048 <= 00004948
@00003018: $ 8 <= 00000049
@00003020: $ 8 <= 0000004a
@00003010: $ 8 <= 0000004a
@00003014: *00000048 <= 004a4948
@00003018: $ 8 <= 0000004a
@00003020: $ 8 <= 0000004b
@00003010: $ 8 <= 0000004b
@00003014: *00000048 <= 4b4a4948
@00003018: $ 8 <= 0000004b
@00003020: $ 8 <= 0000004c
@00003010: $ 8 <= 0000004c
@00003014: *0000004c <= 0000004c
@00003018: $ 8 <= 0000004c
@00003020: $ 8 <= 0000004d
@00003010: $ 8 <= 0000004d
@00003014: *0000004c <= 00004d4c
@00003018: $ 8 <= 0000004d
@00003020: $ 8 <= 0000004e
@00003010: $ 8 <= 0000004e
@00003014: *0000004c <= 004e4d4c
@00003018: $ 8 <= 0000004e
@00003020: $ 8 <= 0000004f
@00003010: $ 8 <= 0000004f
@00003014: *0000004c <= 4f4e4d4c
@00003018: $ 8 <= 0000004f
@00003020: $ 8 <= 00000050
@00003010: $ 8 <= 00000050
@00003014: *00000050 <= 00000050
@00003018: $ 8 <= 00000050
@00003020: $ 8 <= 00000051
@00003010: $ 8 <= 00000051
@00003014: *00000050 <= 00005150
@00003018: $ 8 <= 00000051
@00003020: $ 8 <= 00000052
@00003010: $ 8 <= 00000052
@00003014: *00000050 <= 00525150
@00003018: $ 8 <= 00000052
@00003020: $ 8 <= 00000053
@00003010: $ 8 <= 00000053
@00003014: *00000050 <= 53525150
@00003018: $ 8 <= 00000053
@00003020: $ 8 <= 00000054
@00003010: $ 8 <= 00000054
@00003014: *00000054 <= 00000054
@00003018: $ 8 <= 00000054
@00003020: $ 8 <= 00000055
@00003010: $ 8 <= 00000055
@00003014: *00000054 <= 00005554
@00003018: $ 8 <= 00000055
@00003020: $ 8 <= 00000056
@00003010: $ 8 <= 00000056
@00003014: *00000054 <= 00565554
@00003018: $ 8 <= 00000056
@00003020: $ 8 <= 00000057
@00003010: $ 8 <= 00000057
@00003014: *00000054 <= 57565554
@00003018: $ 8 <= 00000057
@00003020: $ 8 <= 00000058
@00003010: $ 8 <= 00000058
@00003014: *00000058 <= 00000058
@00003018: $ 8 <= 00000058
```

```
@00003020: $ 8 <= 00000059
@00003010: $ 8 <= 00000059
@00003014: *00000058 <= 00005958
@00003018: $ 8 <= 00000059
@00003020: $ 8 <= 0000005a
@00003010: $ 8 <= 0000005a
@00003014: *00000058 <= 005a5958
@00003018: $ 8 <= 0000005a
@00003020: $ 8 <= 0000005b
@00003010: $ 8 <= 0000005b
@00003014: *00000058 <= 5b5a5958
@00003018: $ 8 <= 0000005b
@00003020: $ 8 <= 0000005c
@00003010: $ 8 <= 0000005c
@00003014: *0000005c <= 0000005c
@00003018: $ 8 <= 0000005c
@00003020: $ 8 <= 0000005d
@00003010: $ 8 <= 0000005d
@00003014: *0000005c <= 00005d5c
@00003018: $ 8 <= 0000005d
@00003020: $ 8 <= 0000005e
@00003010: $ 8 <= 0000005e
@00003014: *0000005c <= 005e5d5c
@00003018: $ 8 <= 0000005e
@00003020: $ 8 <= 0000005f
@00003010: $ 8 <= 0000005f
@00003014: *0000005c <= 5f5e5d5c
@00003018: $ 8 <= 0000005f
@00003020: $ 8 <= 00000060
@00003010: $ 8 <= 00000060
@00003014: *00000060 <= 00000060
@00003018: $ 8 <= 00000060
@00003020: $ 8 <= 00000061
@00003010: $ 8 <= 00000061
@00003014: *00000060 <= 00006160
@00003018: $ 8 <= 00000061
@00003020: $ 8 <= 00000062
@00003010: $ 8 <= 00000062
@00003014: *00000060 <= 00626160
@00003018: $ 8 <= 00000062
@00003020: $ 8 <= 00000063
@00003010: $ 8 <= 00000063
@00003014: *00000060 <= 63626160
@00003018: $ 8 <= 00000063
@00003020: $ 8 <= 00000064
@00003010: $ 8 <= 00000064
@00003014: *00000064 <= 00000064
@00003018: $ 8 <= 00000064
@00003020: $ 8 <= 00000065
@00003010: $ 8 <= 00000065
@00003014: *00000064 <= 00006564
@00003018: $ 8 <= 00000065
@00003020: $ 8 <= 00000066
@00003010: $ 8 <= 00000066
@00003014: *00000064 <= 00666564
@00003018: $ 8 <= 00000066
@00003020: $ 8 <= 00000067
@00003010: $ 8 <= 00000067
@00003014: *00000064 <= 67666564
@00003018: $ 8 <= 00000067
@00003020: $ 8 <= 00000068
@00003010: $ 8 <= 00000068
@00003014: *00000068 <= 00000068
@00003018: $ 8 <= 00000068
@00003020: $ 8 <= 00000069
@00003010: $ 8 <= 00000069
@00003014: *00000068 <= 00006968
@00003018: $ 8 <= 00000069
@00003020: $ 8 <= 0000006a
@00003010: $ 8 <= 0000006a
@00003014: *00000068 <= 006a6968
@00003018: $ 8 <= 0000006a
@00003020: $ 8 <= 0000006b
@00003010: $ 8 <= 0000006b
@00003014: *00000068 <= 6b6a6968
@00003018: $ 8 <= 0000006b
@00003020: $ 8 <= 0000006c
@00003010: $ 8 <= 0000006c
@00003014: *0000006c <= 0000006c
@00003018: $ 8 <= 0000006c
@00003020: $ 8 <= 0000006d
@00003010: $ 8 <= 0000006d
@00003014: *0000006c <= 00006d6c
@00003018: $ 8 <= 0000006d
@00003020: $ 8 <= 0000006e
```

```
@00003010: $ 8 <= 0000006e
@00003014: *0000006c <= 006e6d6c
@00003018: $ 8 <= 0000006e
@00003020: $ 8 <= 0000006f
@00003010: $ 8 <= 0000006f
@00003014: *0000006c <= 6f6e6d6c
@00003018: $ 8 <= 0000006f
@00003020: $ 8 <= 00000070
@00003010: $ 8 <= 00000070
@00003014: *00000070 <= 00000070
@00003018: $ 8 <= 00000070
@00003020: $ 8 <= 00000071
@00003010: $ 8 <= 00000071
@00003014: *00000070 <= 00007170
@00003018: $ 8 <= 00000071
@00003020: $ 8 <= 00000072
@00003010: $ 8 <= 00000072
@00003014: *00000070 <= 00727170
@00003018: $ 8 <= 00000072
@00003020: $ 8 <= 00000073
@00003010: $ 8 <= 00000073
@00003014: *00000070 <= 73727170
@00003018: $ 8 <= 00000073
@00003020: $ 8 <= 00000074
@00003010: $ 8 <= 00000074
@00003014: *00000074 <= 00000074
@00003018: $ 8 <= 00000074
@00003020: $ 8 <= 00000075
@00003010: $ 8 <= 00000075
@00003014: *00000074 <= 00007574
@00003018: $ 8 <= 00000075
@00003020: $ 8 <= 00000076
@00003010: $ 8 <= 00000076
@00003014: *00000074 <= 00767574
@00003018: $ 8 <= 00000076
@00003020: $ 8 <= 00000077
@00003010: $ 8 <= 00000077
@00003014: *00000074 <= 77767574
@00003018: $ 8 <= 00000077
@00003020: $ 8 <= 00000078
@00003010: $ 8 <= 00000078
@00003014: *00000078 <= 00000078
@00003018: $ 8 <= 00000078
@00003020: $ 8 <= 00000079
@00003010: $ 8 <= 00000079
@00003014: *00000078 <= 00007978
@00003018: $ 8 <= 00000079
@00003020: $ 8 <= 0000007a
@00003010: $ 8 <= 0000007a
@00003014: *00000078 <= 007a7978
@00003018: $ 8 <= 0000007a
@00003020: $ 8 <= 0000007b
@00003010: $ 8 <= 0000007b
@00003014: *00000078 <= 7b7a7978
@00003018: $ 8 <= 0000007b
@00003020: $ 8 <= 0000007c
@00003010: $ 8 <= 0000007c
@00003014: *0000007c <= 0000007c
@00003018: $ 8 <= 0000007c
@00003020: $ 8 <= 0000007d
@00003010: $ 8 <= 0000007d
@00003014: *0000007c <= 00007d7c
@00003018: $ 8 <= 0000007d
@00003020: $ 8 <= 0000007e
@00003010: $ 8 <= 0000007e
@00003014: *0000007c <= 007e7d7c
@00003018: $ 8 <= 0000007e
@00003020: $ 8 <= 0000007f
@00003010: $ 8 <= 0000007f
@00003014: *0000007c <= 7f7e7d7c
@00003018: $ 8 <= 0000007f
@00003020: $ 8 <= 00000080
@00003010: $ 8 <= 00000080
@00003014: *00000080 <= 00000080
@00003018: $ 8 <= 00000080
@00003020: $ 8 <= 00000081
@00003010: $ 8 <= 00000081
@00003014: *00000080 <= 00008180
@00003018: $ 8 <= 00000081
@00003020: $ 8 <= 00000082
@00003010: $ 8 <= 00000082
@00003014: *00000080 <= 00828180
@00003018: $ 8 <= 00000082
@00003020: $ 8 <= 00000083
@00003010: $ 8 <= 00000083
```

```
@00003014: *00000080 <= 83828180
@00003018: $ 8 <= 00000083
@00003020: $ 8 <= 00000084
@00003010: $ 8 <= 00000084
@00003014: *00000084 <= 00000084
@00003018: $ 8 <= 00000084
@00003020: $ 8 <= 00000085
@00003010: $ 8 <= 00000085
@00003014: *00000084 <= 00008584
@00003018: $ 8 <= 00000085
@00003020: $ 8 <= 00000086
@00003010: $ 8 <= 00000086
@00003014: *00000084 <= 00868584
@00003018: $ 8 <= 00000086
@00003020: $ 8 <= 00000087
@00003010: $ 8 <= 00000087
@00003014: *00000084 <= 87868584
@00003018: $ 8 <= 00000087
@00003020: $ 8 <= 00000088
@00003010: $ 8 <= 00000088
@00003014: *00000088 <= 00000088
@00003018: $ 8 <= 00000088
@00003020: $ 8 <= 00000089
@00003010: $ 8 <= 00000089
@00003014: *00000088 <= 00008988
@00003018: $ 8 <= 00000089
@00003020: $ 8 <= 0000008a
@00003010: $ 8 <= 0000008a
@00003014: *00000088 <= 008a8988
@00003018: $ 8 <= 0000008a
@00003020: $ 8 <= 0000008b
@00003010: $ 8 <= 0000008b
@00003014: *00000088 <= 8b8a8988
@00003018: $ 8 <= 0000008b
@00003020: $ 8 <= 0000008c
@00003010: $ 8 <= 0000008c
@00003014: *0000008c <= 0000008c
@00003018: $ 8 <= 0000008c
@00003020: $ 8 <= 0000008d
@00003010: $ 8 <= 0000008d
@00003014: *0000008c <= 00008d8c
@00003018: $ 8 <= 0000008d
@00003020: $ 8 <= 0000008e
@00003010: $ 8 <= 0000008e
@00003014: *0000008c <= 008e8d8c
@00003018: $ 8 <= 0000008e
@00003020: $ 8 <= 0000008f
@00003010: $ 8 <= 0000008f
@00003014: *0000008c <= 8f8e8d8c
@00003018: $ 8 <= 0000008f
@00003020: $ 8 <= 00000090
@00003010: $ 8 <= 00000090
@00003014: *00000090 <= 00000090
@00003018: $ 8 <= 00000090
@00003020: $ 8 <= 00000091
@00003010: $ 8 <= 00000091
@00003014: *00000090 <= 00009190
@00003018: $ 8 <= 00000091
@00003020: $ 8 <= 00000092
@00003010: $ 8 <= 00000092
@00003014: *00000090 <= 00929190
@00003018: $ 8 <= 00000092
@00003020: $ 8 <= 00000093
@00003010: $ 8 <= 00000093
@00003014: *00000090 <= 93929190
@00003018: $ 8 <= 00000093
@00003020: $ 8 <= 00000094
@00003010: $ 8 <= 00000094
@00003014: *00000094 <= 00000094
@00003018: $ 8 <= 00000094
@00003020: $ 8 <= 00000095
@00003010: $ 8 <= 00000095
@00003014: *00000094 <= 00009594
@00003018: $ 8 <= 00000095
@00003020: $ 8 <= 00000096
@00003010: $ 8 <= 00000096
@00003014: *00000094 <= 00969594
@00003018: $ 8 <= 00000096
@00003020: $ 8 <= 00000097
@00003010: $ 8 <= 00000097
@00003014: *00000094 <= 97969594
@00003018: $ 8 <= 00000097
@00003020: $ 8 <= 00000098
@00003010: $ 8 <= 00000098
@00003014: *00000098 <= 00000098
```

```
@00003018: $ 8 <= 00000098
@00003020: $ 8 <= 00000099
@00003010: $ 8 <= 00000099
@00003014: *00000098 <= 00009998
@00003018: $ 8 <= 00000099
@00003020: $ 8 <= 0000009a
@00003010: $ 8 <= 0000009a
@00003014: *00000098 <= 009a9998
@00003018: $ 8 <= 0000009a
@00003020: $ 8 <= 0000009b
@00003010: $ 8 <= 0000009b
@00003014: *00000098 <= 9b9a9998
@00003018: $ 8 <= 0000009b
@00003020: $ 8 <= 0000009c
@00003010: $ 8 <= 0000009c
@00003014: *0000009c <= 0000009c
@00003018: $ 8 <= 0000009c
@00003020: $ 8 <= 0000009d
@00003010: $ 8 <= 0000009d
@00003014: *0000009c <= 00009d9c
@00003018: $ 8 <= 0000009d
@00003020: $ 8 <= 0000009e
@00003010: $ 8 <= 0000009e
@00003014: *0000009c <= 009e9d9c
@00003018: $ 8 <= 0000009e
@00003020: $ 8 <= 0000009f
@00003010: $ 8 <= 0000009f
@00003014: *0000009c <= 9f9e9d9c
@00003018: $ 8 <= 0000009f
@00003020: $ 8 <= 000000a0
@00003010: $ 8 <= 000000a0
@00003014: *000000a0 <= 000000a0
@00003018: $ 8 <= 000000a0
@00003020: $ 8 <= 000000a1
@00003010: $ 8 <= 000000a1
@00003014: *000000a0 <= 0000a1a0
@00003018: $ 8 <= 000000a1
@00003020: $ 8 <= 000000a2
@00003010: $ 8 <= 000000a2
@00003014: *000000a0 <= 00a2a1a0
@00003018: $ 8 <= 000000a2
@00003020: $ 8 <= 000000a3
@00003010: $ 8 <= 000000a3
@00003014: *000000a0 <= a3a2a1a0
@00003018: $ 8 <= 000000a3
@00003020: $ 8 <= 000000a4
@00003010: $ 8 <= 000000a4
@00003014: *000000a4 <= 000000a4
@00003018: $ 8 <= 000000a4
@00003020: $ 8 <= 000000a5
@00003010: $ 8 <= 000000a5
@00003014: *000000a4 <= 0000a5a4
@00003018: $ 8 <= 000000a5
@00003020: $ 8 <= 000000a6
@00003010: $ 8 <= 000000a6
@00003014: *000000a4 <= 00a6a5a4
@00003018: $ 8 <= 000000a6
@00003020: $ 8 <= 000000a7
@00003010: $ 8 <= 000000a7
@00003014: *000000a4 <= a7a6a5a4
@00003018: $ 8 <= 000000a7
@00003020: $ 8 <= 000000a8
@00003010: $ 8 <= 000000a8
@00003014: *000000a8 <= 000000a8
@00003018: $ 8 <= 000000a8
@00003020: $ 8 <= 000000a9
@00003010: $ 8 <= 000000a9
@00003014: *000000a8 <= 0000a9a8
@00003018: $ 8 <= 000000a9
@00003020: $ 8 <= 000000aa
@00003010: $ 8 <= 000000aa
@00003014: *000000a8 <= 00aaa9a8
@00003018: $ 8 <= 000000aa
@00003020: $ 8 <= 000000ab
@00003010: $ 8 <= 000000ab
@00003014: *000000a8 <= abaaa9a8
@00003018: $ 8 <= 000000ab
@00003020: $ 8 <= 000000ac
@00003010: $ 8 <= 000000ac
@00003014: *000000ac <= 000000ac
@00003018: $ 8 <= 000000ac
@00003020: $ 8 <= 000000ad
@00003010: $ 8 <= 000000ad
@00003014: *000000ac <= 0000adac
@00003018: $ 8 <= 000000ad
```

```
@00003020: $ 8 <= 000000ae
@00003010: $ 8 <= 000000ae
@00003014: *000000ac <= 00aeadac
@00003018: $ 8 <= 000000ae
@00003020: $ 8 <= 000000af
@00003010: $ 8 <= 000000af
@00003014: *000000ac <= afaeadac
@00003018: $ 8 <= 000000af
@00003020: $ 8 <= 000000b0
@00003010: $ 8 <= 000000b0
@00003014: *000000b0 <= 000000b0
@00003018: $ 8 <= 000000b0
@00003020: $ 8 <= 000000b1
@00003010: $ 8 <= 000000b1
@00003014: *000000b0 <= 0000b1b0
@00003018: $ 8 <= 000000b1
@00003020: $ 8 <= 000000b2
@00003010: $ 8 <= 000000b2
@00003014: *000000b0 <= 00b2b1b0
@00003018: $ 8 <= 000000b2
@00003020: $ 8 <= 000000b3
@00003010: $ 8 <= 000000b3
@00003014: *000000b0 <= b3b2b1b0
@00003018: $ 8 <= 000000b3
@00003020: $ 8 <= 000000b4
@00003010: $ 8 <= 000000b4
@00003014: *000000b4 <= 000000b4
@00003018: $ 8 <= 000000b4
@00003020: $ 8 <= 000000b5
@00003010: $ 8 <= 000000b5
@00003014: *000000b4 <= 0000b5b4
@00003018: $ 8 <= 000000b5
@00003020: $ 8 <= 000000b6
@00003010: $ 8 <= 000000b6
@00003014: *000000b4 <= 00b6b5b4
@00003018: $ 8 <= 000000b6
@00003020: $ 8 <= 000000b7
@00003010: $ 8 <= 000000b7
@00003014: *000000b4 <= b7b6b5b4
@00003018: $ 8 <= 000000b7
@00003020: $ 8 <= 000000b8
@00003010: $ 8 <= 000000b8
@00003014: *000000b8 <= 000000b8
@00003018: $ 8 <= 000000b8
@00003020: $ 8 <= 000000b9
@00003010: $ 8 <= 000000b9
@00003014: *000000b8 <= 0000b9b8
@00003018: $ 8 <= 000000b9
@00003020: $ 8 <= 000000ba
@00003010: $ 8 <= 000000ba
@00003014: *000000b8 <= 00bab9b8
@00003018: $ 8 <= 000000ba
@00003020: $ 8 <= 000000bb
@00003010: $ 8 <= 000000bb
@00003014: *000000b8 <= bbbab9b8
@00003018: $ 8 <= 000000bb
@00003020: $ 8 <= 000000bc
@00003010: $ 8 <= 000000bc
@00003014: *000000bc <= 000000bc
@00003018: $ 8 <= 000000bc
@00003020: $ 8 <= 000000bd
@00003010: $ 8 <= 000000bd
@00003014: *000000bc <= 0000bdbc
@00003018: $ 8 <= 000000bd
@00003020: $ 8 <= 000000be
@00003010: $ 8 <= 000000be
@00003014: *000000bc <= 00bebdbc
@00003018: $ 8 <= 000000be
@00003020: $ 8 <= 000000bf
@00003010: $ 8 <= 000000bf
@00003014: *000000bc <= bfbebdbc
@00003018: $ 8 <= 000000bf
@00003020: $ 8 <= 000000c0
@00003010: $ 8 <= 000000c0
@00003014: *000000c0 <= 000000c0
@00003018: $ 8 <= 000000c0
@00003020: $ 8 <= 000000c1
@00003010: $ 8 <= 000000c1
@00003014: *000000c0 <= 0000c1c0
@00003018: $ 8 <= 000000c1
@00003020: $ 8 <= 000000c2
@00003010: $ 8 <= 000000c2
@00003014: *000000c0 <= 00c2c1c0
@00003018: $ 8 <= 000000c2
@00003020: $ 8 <= 000000c3
```

```
@00003010: $ 8 <= 000000c3
@00003014: *000000c0 <= c3c2c1c0
@00003018: $ 8 <= 000000c3
@00003020: $ 8 <= 000000c4
@00003010: $ 8 <= 000000c4
@00003014: *000000c4 <= 000000c4
@00003018: $ 8 <= 000000c4
@00003020: $ 8 <= 000000c5
@00003010: $ 8 <= 000000c5
@00003014: *000000c4 <= 0000c5c4
@00003018: $ 8 <= 000000c5
@00003020: $ 8 <= 000000c6
@00003010: $ 8 <= 000000c6
@00003014: *000000c4 <= 00c6c5c4
@00003018: $ 8 <= 000000c6
@00003020: $ 8 <= 000000c7
@00003010: $ 8 <= 000000c7
@00003014: *000000c4 <= c7c6c5c4
@00003018: $ 8 <= 000000c7
@00003020: $ 8 <= 000000c8
@00003010: $ 8 <= 000000c8
@00003014: *000000c8 <= 000000c8
@00003018: $ 8 <= 000000c8
@00003020: $ 8 <= 000000c9
@00003010: $ 8 <= 000000c9
@00003014: *000000c8 <= 0000c9c8
@00003018: $ 8 <= 000000c9
@00003020: $ 8 <= 000000ca
@00003010: $ 8 <= 000000ca
@00003014: *000000c8 <= 00cac9c8
@00003018: $ 8 <= 000000ca
@00003020: $ 8 <= 000000cb
@00003010: $ 8 <= 000000cb
@00003014: *000000c8 <= cbcac9c8
@00003018: $ 8 <= 000000cb
@00003020: $ 8 <= 000000cc
@00003010: $ 8 <= 000000cc
@00003014: *000000cc <= 000000cc
@00003018: $ 8 <= 000000cc
@00003020: $ 8 <= 000000cd
@00003010: $ 8 <= 000000cd
@00003014: *000000cc <= 0000cdcc
@00003018: $ 8 <= 000000cd
@00003020: $ 8 <= 000000ce
@00003010: $ 8 <= 000000ce
@00003014: *000000cc <= 00cecdcc
@00003018: $ 8 <= 000000ce
@00003020: $ 8 <= 000000cf
@00003010: $ 8 <= 000000cf
@00003014: *000000cc <= cfcecdcc
@00003018: $ 8 <= 000000cf
@00003020: $ 8 <= 000000d0
@00003010: $ 8 <= 000000d0
@00003014: *000000d0 <= 000000d0
@00003018: $ 8 <= 000000d0
@00003020: $ 8 <= 000000d1
@00003010: $ 8 <= 000000d1
@00003014: *000000d0 <= 0000d1d0
@00003018: $ 8 <= 000000d1
@00003020: $ 8 <= 000000d2
@00003010: $ 8 <= 000000d2
@00003014: *000000d0 <= 00d2d1d0
@00003018: $ 8 <= 000000d2
@00003020: $ 8 <= 000000d3
@00003010: $ 8 <= 000000d3
@00003014: *000000d0 <= d3d2d1d0
@00003018: $ 8 <= 000000d3
@00003020: $ 8 <= 000000d4
@00003010: $ 8 <= 000000d4
@00003014: *000000d4 <= 000000d4
@00003018: $ 8 <= 000000d4
@00003020: $ 8 <= 000000d5
@00003010: $ 8 <= 000000d5
@00003014: *000000d4 <= 0000d5d4
@00003018: $ 8 <= 000000d5
@00003020: $ 8 <= 000000d6
@00003010: $ 8 <= 000000d6
@00003014: *000000d4 <= 00d6d5d4
@00003018: $ 8 <= 000000d6
@00003020: $ 8 <= 000000d7
@00003010: $ 8 <= 000000d7
@00003014: *000000d4 <= d7d6d5d4
@00003018: $ 8 <= 000000d7
@00003020: $ 8 <= 000000d8
@00003010: $ 8 <= 000000d8
```

```
@00003014: *000000d8 <= 000000d8
@00003018: $ 8 <= 000000d8
@00003020: $ 8 <= 000000d9
@00003010: $ 8 <= 000000d9
@00003014: *000000d8 <= 0000d9d8
@00003018: $ 8 <= 000000d9
@00003020: $ 8 <= 000000da
@00003010: $ 8 <= 000000da
@00003014: *000000d8 <= 00dad9d8
@00003018: $ 8 <= 000000da
@00003020: $ 8 <= 000000db
@00003010: $ 8 <= 000000db
@00003014: *000000d8 <= dbdad9d8
@00003018: $ 8 <= 000000db
@00003020: $ 8 <= 000000dc
@00003010: $ 8 <= 000000dc
@00003014: *000000dc <= 000000dc
@00003018: $ 8 <= 000000dc
@00003020: $ 8 <= 000000dd
@00003010: $ 8 <= 000000dd
@00003014: *000000dc <= 0000dddc
@00003018: $ 8 <= 000000dd
@00003020: $ 8 <= 000000de
@00003010: $ 8 <= 000000de
@00003014: *000000dc <= 00dedddc
@00003018: $ 8 <= 000000de
@00003020: $ 8 <= 000000df
@00003010: $ 8 <= 000000df
@00003014: *000000dc <= dfdedddc
@00003018: $ 8 <= 000000df
@00003020: $ 8 <= 000000e0
@00003010: $ 8 <= 000000e0
@00003014: *000000e0 <= 000000e0
@00003018: $ 8 <= 000000e0
@00003020: $ 8 <= 000000e1
@00003010: $ 8 <= 000000e1
@00003014: *000000e0 <= 0000e1e0
@00003018: $ 8 <= 000000e1
@00003020: $ 8 <= 000000e2
@00003010: $ 8 <= 000000e2
@00003014: *000000e0 <= 00e2e1e0
@00003018: $ 8 <= 000000e2
@00003020: $ 8 <= 000000e3
@00003010: $ 8 <= 000000e3
@00003014: *000000e0 <= e3e2e1e0
@00003018: $ 8 <= 000000e3
@00003020: $ 8 <= 000000e4
@00003010: $ 8 <= 000000e4
@00003014: *000000e4 <= 000000e4
@00003018: $ 8 <= 000000e4
@00003020: $ 8 <= 000000e5
@00003010: $ 8 <= 000000e5
@00003014: *000000e4 <= 0000e5e4
@00003018: $ 8 <= 000000e5
@00003020: $ 8 <= 000000e6
@00003010: $ 8 <= 000000e6
@00003014: *000000e4 <= 00e6e5e4
@00003018: $ 8 <= 000000e6
@00003020: $ 8 <= 000000e7
@00003010: $ 8 <= 000000e7
@00003014: *000000e4 <= e7e6e5e4
@00003018: $ 8 <= 000000e7
@00003020: $ 8 <= 000000e8
@00003010: $ 8 <= 000000e8
@00003014: *000000e8 <= 000000e8
@00003018: $ 8 <= 000000e8
@00003020: $ 8 <= 000000e9
@00003010: $ 8 <= 000000e9
@00003014: *000000e8 <= 0000e9e8
@00003018: $ 8 <= 000000e9
@00003020: $ 8 <= 000000ea
@00003010: $ 8 <= 000000ea
@00003014: *000000e8 <= 00eae9e8
@00003018: $ 8 <= 000000ea
@00003020: $ 8 <= 000000eb
@00003010: $ 8 <= 000000eb
@00003014: *000000e8 <= ebeae9e8
@00003018: $ 8 <= 000000eb
@00003020: $ 8 <= 000000ec
@00003010: $ 8 <= 000000ec
@00003014: *000000ec <= 000000ec
@00003018: $ 8 <= 000000ec
@00003020: $ 8 <= 000000ed
@00003010: $ 8 <= 000000ed
@00003014: *000000ec <= 0000edec
```

```
@00003018: $ 8 <= 000000ed
@00003020: $ 8 <= 000000ee
@00003010: $ 8 <= 000000ee
@00003014: *000000ec <= 00eeedec
@00003018: $ 8 <= 000000ee
@00003020: $ 8 <= 000000ef
@00003010: $ 8 <= 000000ef
@00003014: *000000ec <= efeeedec
@00003018: $ 8 <= 000000ef
@00003020: $ 8 <= 000000f0
@00003010: $ 8 <= 000000f0
@00003014: *000000f0 <= 000000f0
@00003018: $ 8 <= 000000f0
@00003020: $ 8 <= 000000f1
@00003010: $ 8 <= 000000f1
@00003014: *000000f0 <= 0000f1f0
@00003018: $ 8 <= 000000f1
@00003020: $ 8 <= 000000f2
@00003010: $ 8 <= 000000f2
@00003014: *000000f0 <= 00f2f1f0
@00003018: $ 8 <= 000000f2
@00003020: $ 8 <= 000000f3
@00003010: $ 8 <= 000000f3
@00003014: *000000f0 <= f3f2f1f0
@00003018: $ 8 <= 000000f3
@00003020: $ 8 <= 000000f4
@00003010: $ 8 <= 000000f4
@00003014: *000000f4 <= 000000f4
@00003018: $ 8 <= 000000f4
@00003020: $ 8 <= 000000f5
@00003010: $ 8 <= 000000f5
@00003014: *000000f4 <= 0000f5f4
@00003018: $ 8 <= 000000f5
@00003020: $ 8 <= 000000f6
@00003010: $ 8 <= 000000f6
@00003014: *000000f4 <= 00f6f5f4
@00003018: $ 8 <= 000000f6
@00003020: $ 8 <= 000000f7
@00003010: $ 8 <= 000000f7
@00003014: *000000f4 <= f7f6f5f4
@00003018: $ 8 <= 000000f7
@00003020: $ 8 <= 000000f8
@00003010: $ 8 <= 000000f8
@00003014: *000000f8 <= 000000f8
@00003018: $ 8 <= 000000f8
@00003020: $ 8 <= 000000f9
@00003010: $ 8 <= 000000f9
@00003014: *000000f8 <= 0000f9f8
@00003018: $ 8 <= 000000f9
@00003020: $ 8 <= 000000fa
@00003010: $ 8 <= 000000fa
@00003014: *000000f8 <= 00faf9f8
@00003018: $ 8 <= 000000fa
@00003020: $ 8 <= 000000fb
@00003010: $ 8 <= 000000fb
@00003014: *000000f8 <= fbfaf9f8
@00003018: $ 8 <= 000000fb
@00003020: $ 8 <= 000000fc
@00003010: $ 8 <= 000000fc
@00003014: *000000fc <= 000000fc
@00003018: $ 8 <= 000000fc
@00003020: $ 8 <= 000000fd
@00003010: $ 8 <= 000000fd
@00003014: *000000fc <= 0000fdfc
@00003018: $ 8 <= 000000fd
@00003020: $ 8 <= 000000fe
@00003010: $ 8 <= 000000fe
@00003014: *000000fc <= 00fefdfc
@00003018: $ 8 <= 000000fe
@00003020: $ 8 <= 000000ff
@00003010: $ 8 <= 000000ff
@00003014: *000000fc <= fffefdfc
@00003018: $ 8 <= 000000ff
@00003020: $ 8 <= 00000100
@00003024: $ 8 <= 00000000
@00003028: $ 4 <= 00000000
@0000302c: $ 9 <= 00000001
@00003030: $ 8 <= 00000001
@00003034: $ 4 <= 00000001
@00003038: $ 9 <= 00000002
@0000303c: $ 8 <= 00000003
@00003040: $ 4 <= 00000003
@00003044: $ 9 <= 00000004
@00003048: $ 8 <= 00000007
@0000304c: $ 4 <= 00000007
```

```
@00003050: $ 9 <= 00000008
@00003054: $ 8 <= 0000000f
@00003058: $ 4 <= 0000000f
@0000305c: $ 9 <= 00000010
@00003060: $ 8 <= 0000001f
@00003064: $ 4 <= 0000001f
@00003068: $ 9 <= 00000020
@0000306c: $ 8 <= 0000003f
```

思考题

1. 为什么需要有单独的乘除法部件而不是整合进 ALU？为何需要有独立的 `HI,LO` 寄存器？

   因为 ALU 是一个 32 位输出端口，而乘除法是两个输出端口 `HI,LO` ，再加上乘除操作的延迟比较高，所以作为独立模块能尽量不减少处理器的效能。

2. 参照你对延迟槽的理解，试解释“乘除槽”。

   与延迟槽相似的地方就是他们俩在 D 级检测到乘除指令就会产生 `start` 信号，并且在下一周期产生 `busy` 信号，若发生冲突就暂停，直到 `busy` 信号无效为止，若不暂停可理解位延迟槽的空指令。

3. 举例说明并分析何时按字节访问内存相对于按字访问内存性能上更有优势。

   在 C 语言中的字符串处理会更为方便，如果按字节访问就只需要直接读出一个字节，若按字访问就需要判断 offset 并选择读取哪一个字节，所以按字节访问相对会快许多。

4. 在本实验中你遇到了哪些不同指令类型组合产生的冲突？你又是如何解决的？相应的测试样例是什么样的？

   如果你是手动构造的样例，请说明构造策略，说明你的测试程序如何保证**覆盖**了所有需要测试的情况；如果你是**完全随机**生成的测试样例，请思考完全随机的测试程序有何不足之处；如果你在生成测试样例时采用了**特殊的策略**，比如构造连续数据冒险序列，请你描述一下你使用的策略如何**结合了随机性**达到强测的效果。

   此思考题请同学们结合自己测试 CPU 使用的具体手段，按照自己的实际情况进行回答

   在 `lb,lbu,lh,lhu` 转发时遇到了一些问题，因和 p5 不同在于他们转发的数据应为 `LoadType` 的输出数据，而不是 `DM` 的输出数据，所以在这里更改了转发端口即可解决。
   在乘除槽的冲突指令利用了 `busy | start` 来判断 D 级指令该不该暂停，以下为测试乘除指令暂停机制的测试代码。

   ```
   mult $t0, $t1
   mfhi $t0
   div $t0, $t1
   mthi $t1
   multu $t0, $t1
   mtlo $t0
   divu $t1, $t0
   mthi $t1
   ```

   该测试代码将所有的乘除槽指令都集中在一起，以便让暂停机制和转发机制能集中进行。

5. 为了对抗复杂性你采取了哪些抽象和规范手段？这些手段在译码和处理数据冲突的时候有什么样的特点与帮助？

   除了命名方面的改善，还利用了 Excel 来将各个指令的 $Tuse$ 和 $Tnew$ 分析了一遍，再写入程序。先把功能模块需要用的接口接线后，先把模块放入数据通路，再实现模块。若模块比较复杂，可以先测一测模块再进一步搭建 CPU 。最后就是代码风格，代码能越简洁就越好，最好是做到看第一眼就知道这一块是干什么的，以便 debug 和修改代码。