笔记前言：

本笔记的内容是去掉步骤的概述后，视频的所有内容。

本猴觉得，自己的步骤概述写的太啰嗦，大家自己做笔记时，

应该每个人都有自己的最舒服最简练的写法，所以没给大家写。

再是本猴觉得，不给大家写这个概述的话，大家会记忆的更深，

掌握的更好！

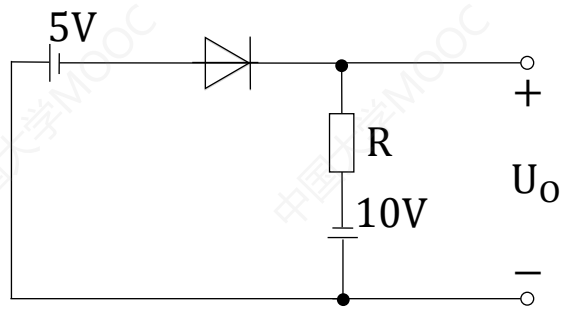
所以老铁！一定要过呀！不要辜负本猴的心意！~~~

【祝逢考必过，心想事成~~~~】

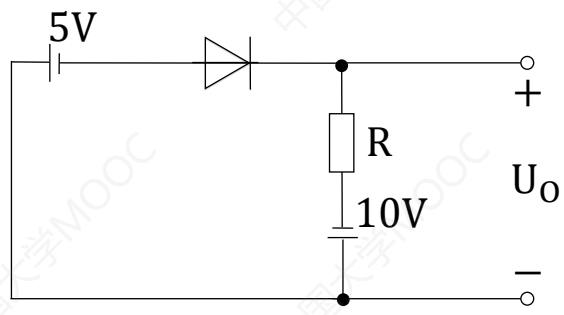
【一定能过！！！！！】

单个二极管的状态分析

例1. 已知二极管电路如图所示，导通电压 $U_D = 0.7V$，试判断二极管是导通还是截止并求输出电压U_O

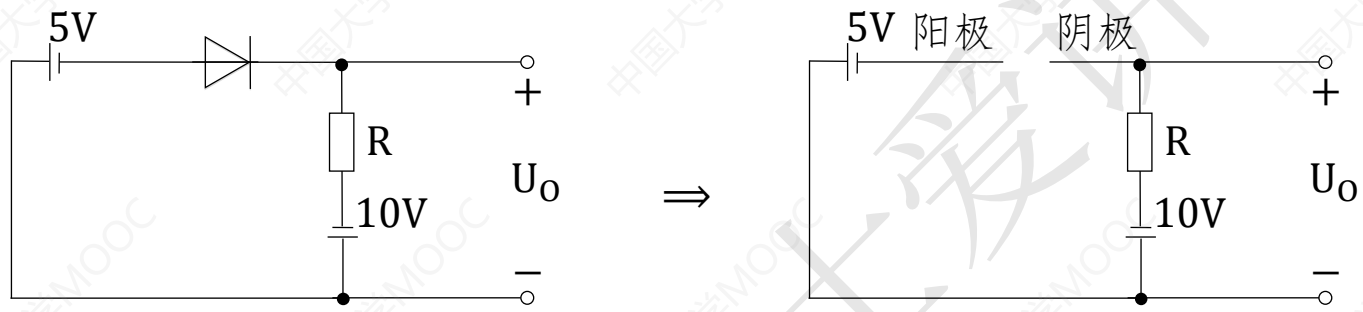


① 把电路图变的完整

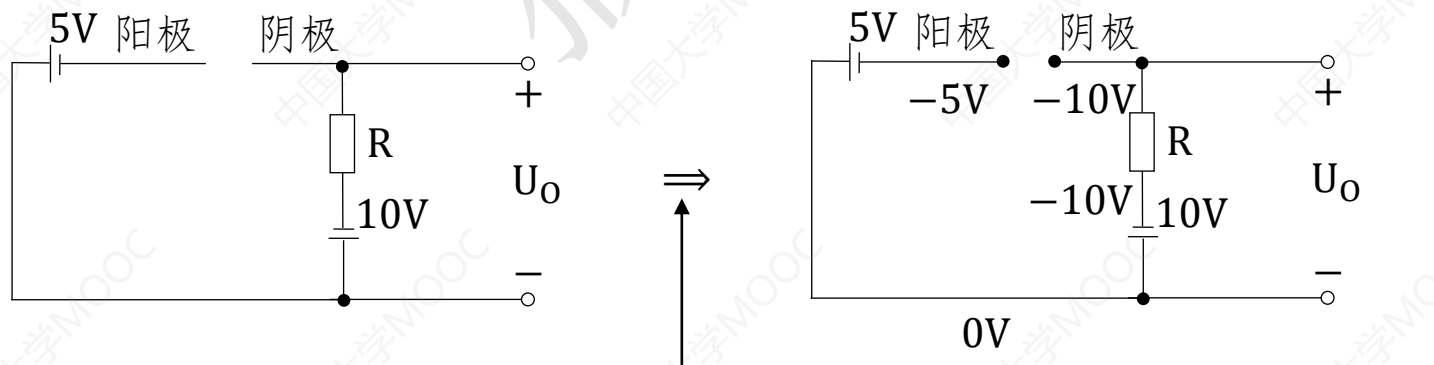


完整电路图

② 把“  ”变成“阳极　阴极”
(此处断开)



③ 分析两极的电位



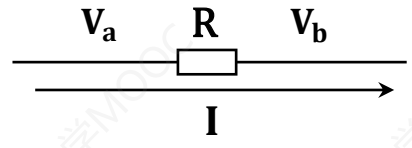
a、确定哪些线上的电位是相同的：线连线，电位就相同

b、若图中有“⊥”，则与其相连部分电位为0

若图中无“⊥”，则与 U_O “−”极相连部分电位为0

c、“

” $\Rightarrow V_a - V_b = A$

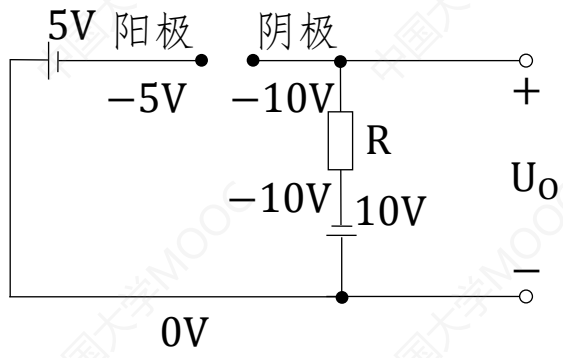
d、忽略 U_O 后， 

： $V_a - V_b = I \cdot R$

【若R不在回路里，$I = 0$，$V_a = V_b$】

④ 若阳极−阴极≥$\mathbf{U_D}$(导通电压，题干没说就**0**)，二极管导通

若阳极−阴极＜$\mathbf{U_D}$(导通电压，题干没说就**0**)，二极管截止



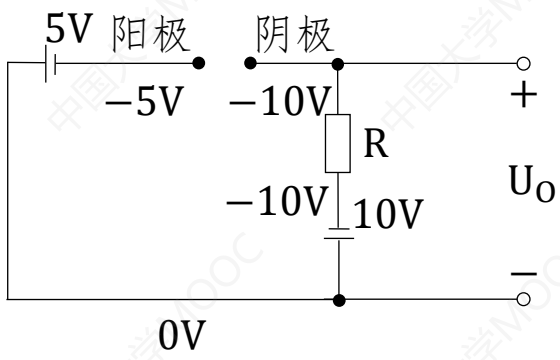
二极管导通

阳极电位−阴极电位$= -5\text{V} - (-10\text{V}) = 5\text{V} > 0.7\text{V}$

⑤ 若二极管截止，跳过本步

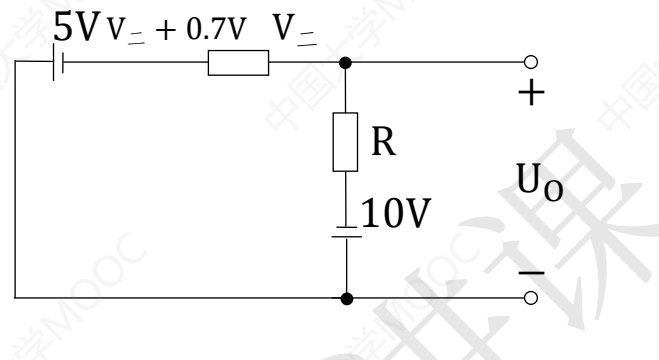
若二极管导通，把“阳极　阴极”变成“$\mathbf{V_{二} + U_D}$　$\mathbf{V_{二}}$”

原来分析的电位作废



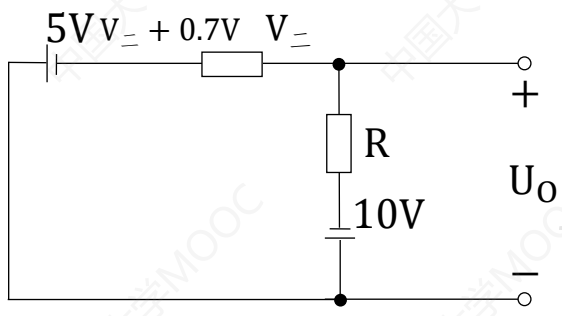
二极管导通

$\Longrightarrow$



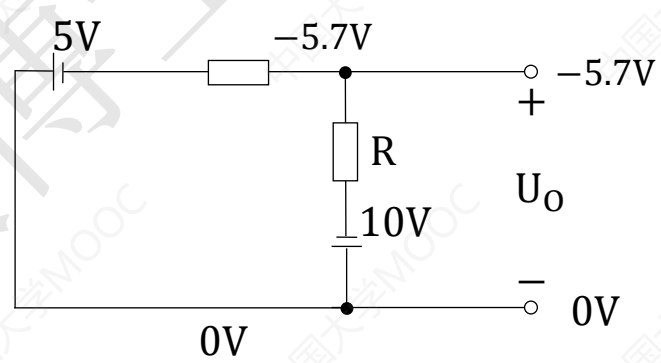
二极管导通

⑥ 分析$\mathbf{U_O}$两端的电位，输出电压$\mathbf{U_O}$＝“+”电位－“−”电位



二极管导通

$\Longrightarrow$



二极管导通

输出电压$U_O = -5.7\text{V} - 0\text{V} = -5.7\text{V}$

a、确定哪些线上的电位是相同的：线连线，电位就相同

b、若图中有“⊥”，则与其相连部分电位为0

若图中无“⊥”，则与$\mathbf{U_O}$“−”极相连部分电位为0

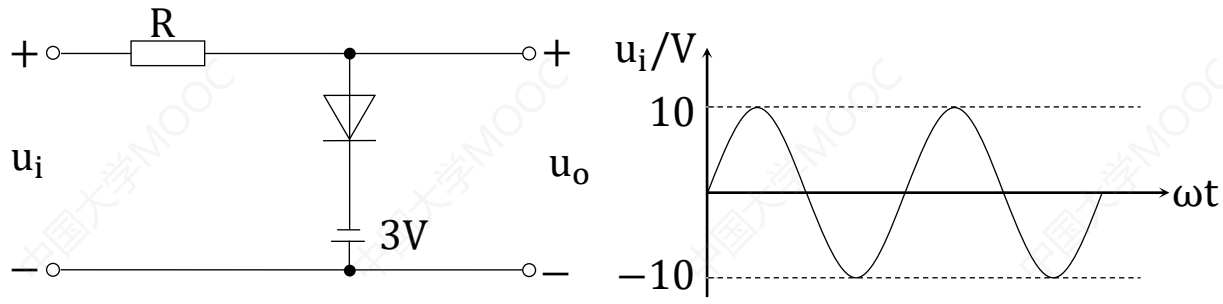
c、“$\mathbf{V_a}$ ⊣⊢ $\mathbf{V_b}$ A V”$\Longrightarrow \mathbf{V_a - V_b = A}$

d、忽略$\mathbf{U_O}$后， $\mathbf{V_a}$ — **R** — $\mathbf{V_b}$ （**I**）：$\mathbf{V_a - V_b = I \cdot R}$

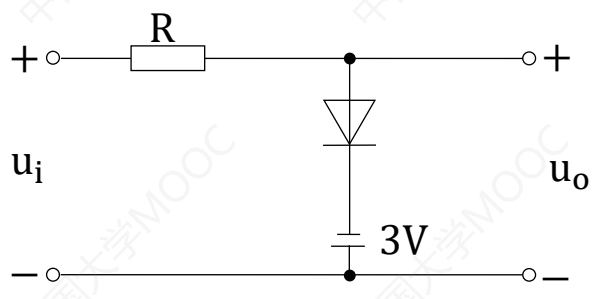
【若R不在回路里，$\mathbf{I = 0}$，$\mathbf{V_a = V_b}$】

单个二极管画输出电压

例1. 已知一个二极管电路如图所示，其中u_i的图像如下，二极管导通电压$U_D=0.7V$，试画出u_o的波形

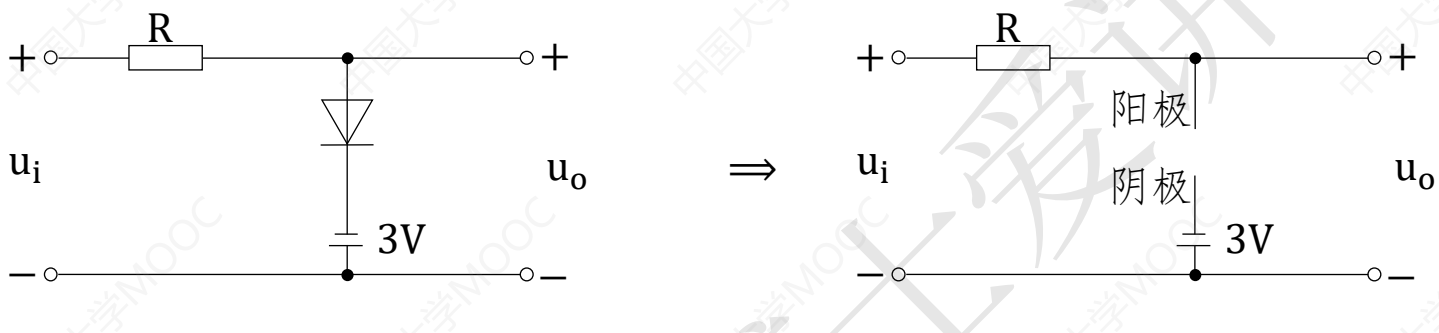


① 把电路图变的完整

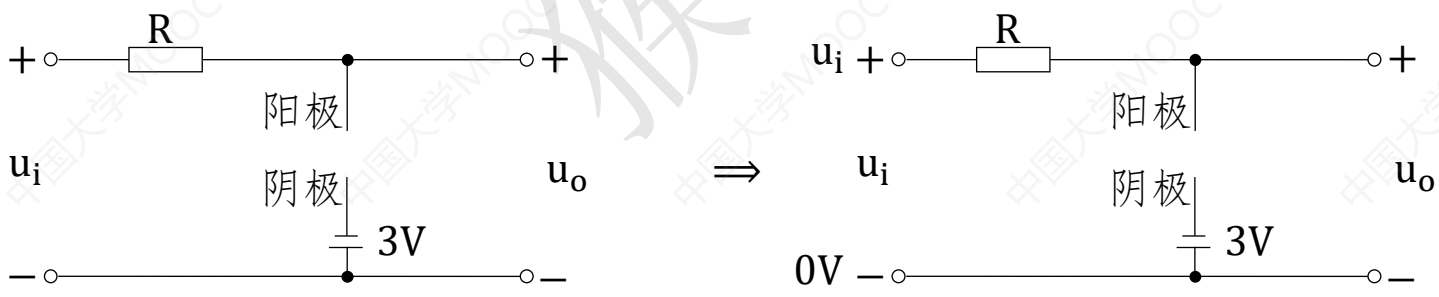


完整电路图

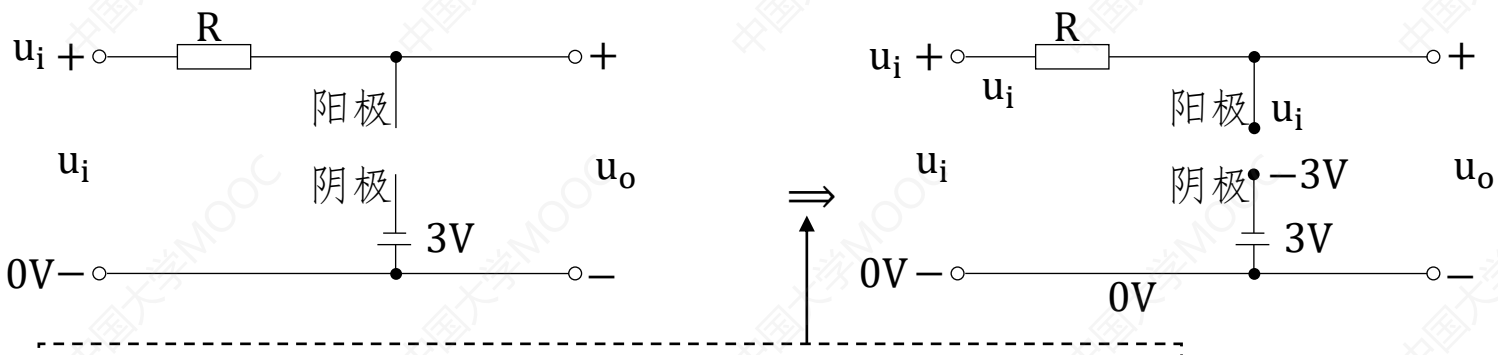
② 把“二极管符号”变成“阳极 阴极（此处断开）”



③ 令 u_i 的“−”极电位为0V，“+”极电位为 u_i



④ 分析两极的电位

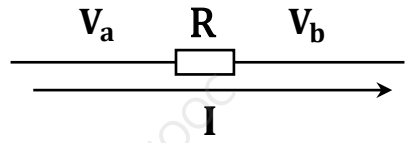


a、确定哪些线上的电位是相同的：线连线，电位就相同

b、若图中有“⊥”，则与其相连部分电位为0

若图中无“⊥”，则与 U_O “−”极相连部分电位为0

c、“$\overset{V_a}{\underset{A}{\dashv\vdash}}\overset{V_b}{\underset{V}{\dashv\vdash}}$” $\Longrightarrow V_a - V_b = A$

d、忽略 U_O 后， 

： $V_a - V_b = I \cdot R$

【若R不在回路里，$I=0$，$V_a = V_b$】

⑤ 求 u_i 满足下面情况时的 u_o(即u_o “+” 电位 − “−” 电位)

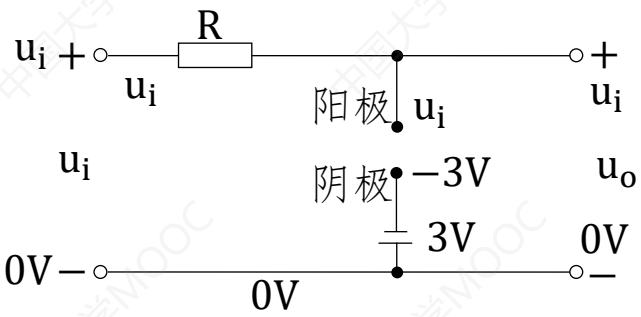
情况一：二极管阳极电位−阴极电位<U_D，

此时正常计算即可

情况二：二极管阳极电位−阴极电位≥U_D，

此时，将 阳极 阴极 变成 $V_{二}+U_D$ $V_{二}$，

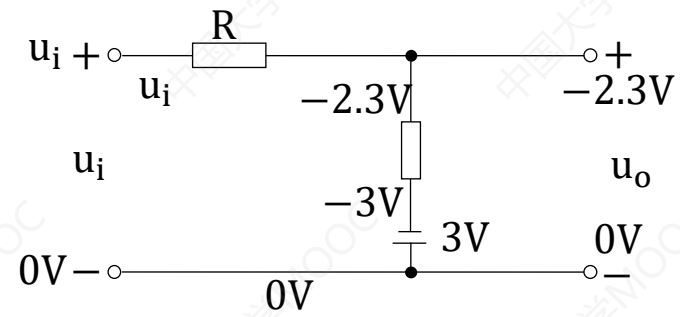
将原来分析的电位作废，再重新分析



情况一：$u_i + 3V < 0.7V \implies u_i < -2.3V$，

此时正常计算 u_o 即可

输出电压 $u_o = u_i - 0V = u_i$



情况二：$u_i + 3V \geq 0.7V, \implies u_i \geq -2.3V$，

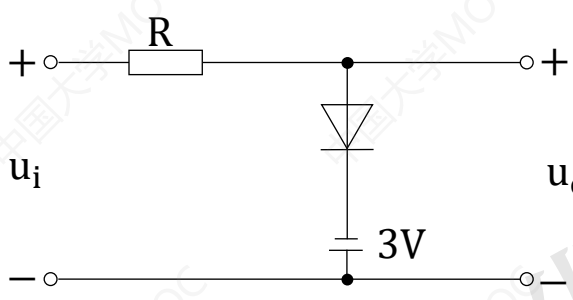
此时，将 阳极 阴极 变成 $V_{二}+U_D$ $V_{二}$，

将原来分析的电位作废，再重新分析

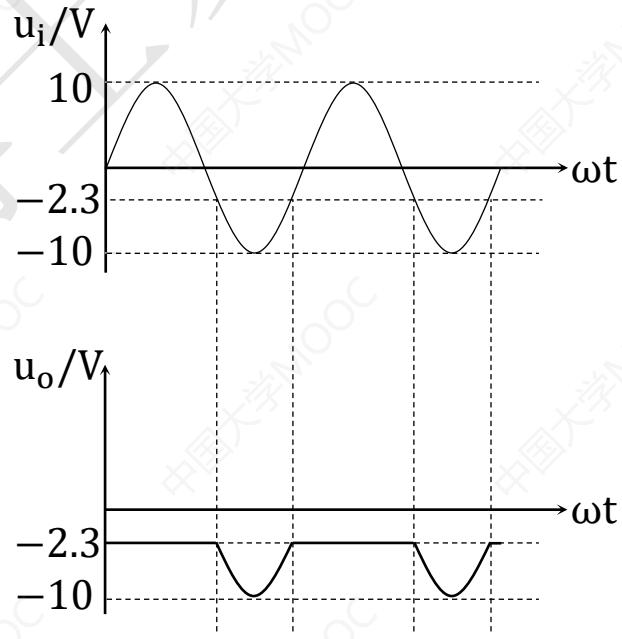
输出电压 $u_o = -2.3V - 0V = -2.3V$

综上：
$$\begin{cases} \text{当 } u_i < -2.3V \text{ 时，} u_o = u_i \\ \text{当 } u_i \geq -2.3V \text{ 时，} u_o = -2.3V \end{cases}$$

⑥ 画出 u_o 的图像

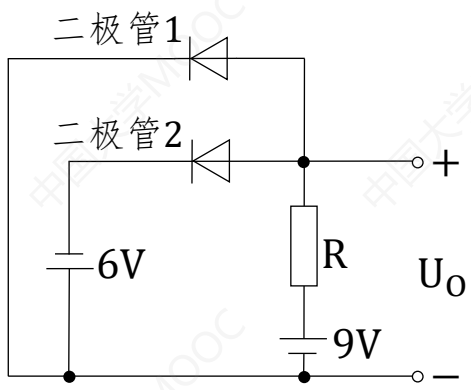


$$\begin{cases} \text{当 } u_i < -2.3V \text{ 时，} u_o = u_i \\ \text{当 } u_i \geq -2.3V \text{ 时，} u_o = -2.3V \end{cases}$$

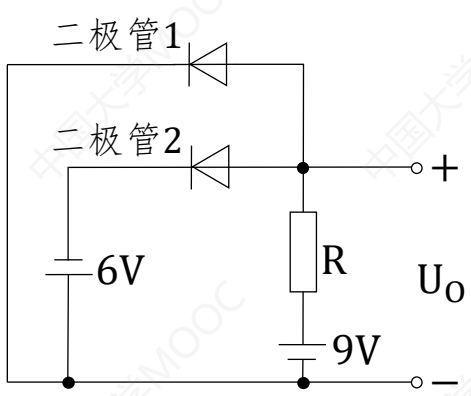


两个二极管的状态分析

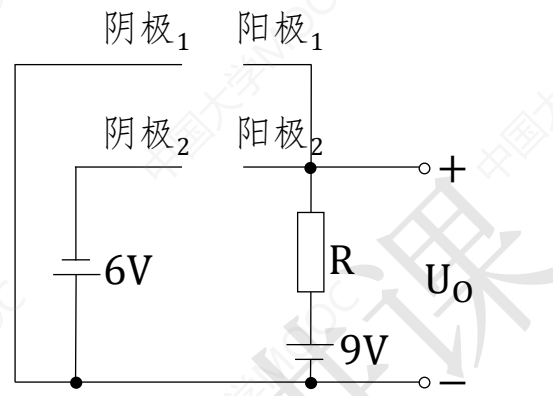
例1. 已知二极管电路如图所示，导通时$U_{D1}=U_{D2}=0.7V$，试判断二极管是导通还是截止并求输出电压U_O



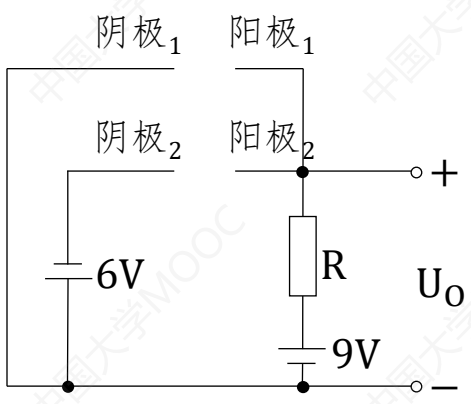
① 把“⊣⊢”变成“阳极 阴极”（此处断开）



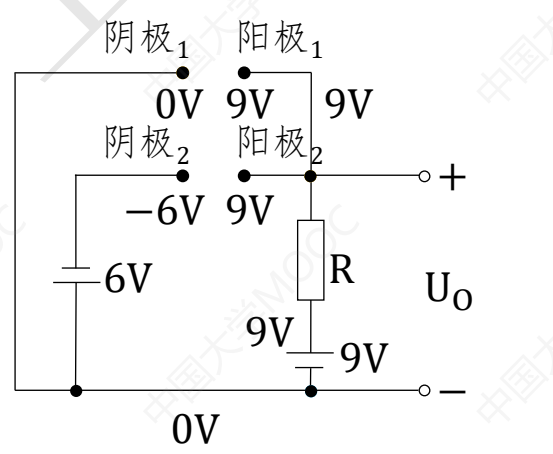
⇒



② 分析两极的电位



⇒



a、确定哪些线上的电位是相同的：线连线，电位就相同

b、若图中有“⊥”，则与其相连部分电位为0

若图中无“⊥”，则与U_O“−”极相连部分电位为0

c、“$\overset{V_a}{\dashv\vdash}\overset{V_b}{}$ A V”$\Rightarrow V_a-V_b=A$

d、忽略U_O后，$\overset{V_a}{\text{—}}\boxed{R}\overset{V_b}{\text{—}}$ I ：$V_a-V_b=I\cdot R$

【若R不在回路里，$I=0$，$V_a=V_b$】

③ 求出各二极管的阳极$_n$ − 阴极$_n$，将结果同它的U_{Dn}作比较

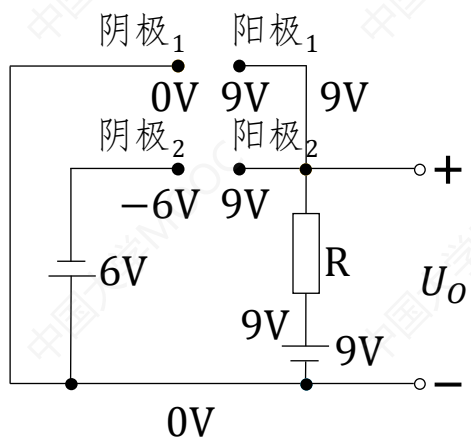
若没有二极管满足阳极$_n$ − 阴极$_n \geq U_{Dn}$，

则对应二极管截止，直接进行第④步；

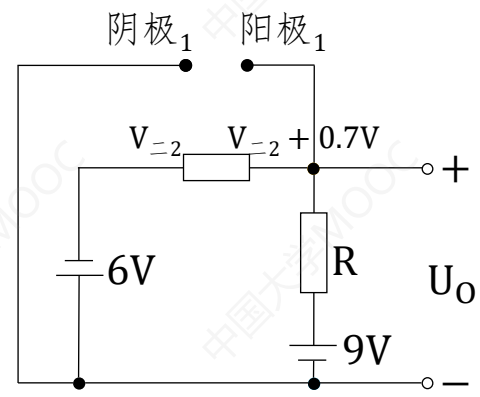
若有二极管满足阳极$_n$ − 阴极$_n \geq U_{Dn}$，

则找出差值结果最大的那个二极管，

把该二极管“阳极$_n$　阴极$_n$”变成“$V_{二n} + U_{Dn}$　$V_{二n}$”，



⇒

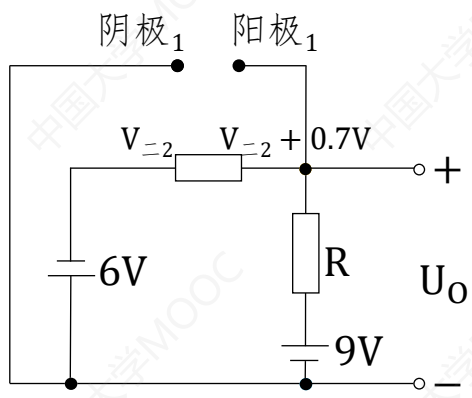


二极管2导通

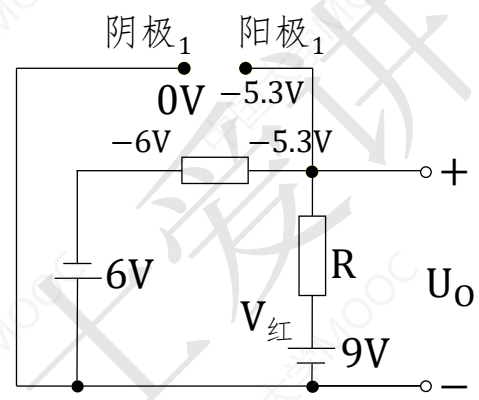
阳极$_1$电位 − 阴极$_1$电位 $= 9V - 0V = 9V > U_{D1} = 0.7V$

阳极$_2$电位 − 阴极$_2$电位 $= 9V - (-6V) = 15V > U_{D2} = 0.7V$

② 分析两极的电位



⇒



二极管2导通

二极管2导通

③ 求出各二极管的阳极$_n$ − 阴极$_n$，将结果同它的U_{Dn}作比较

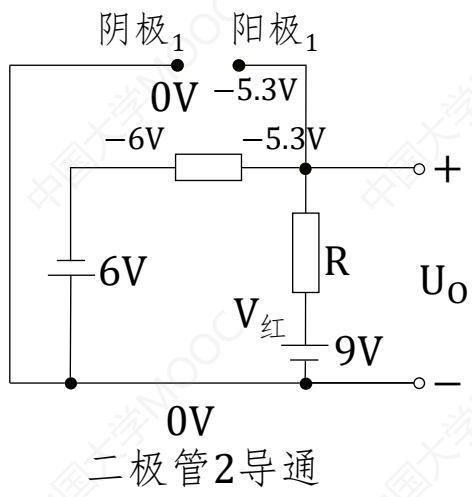
若没有二极管满足阳极$_n$ − 阴极$_n \geq U_{Dn}$，

则对应二极管截止，直接进行第④步；

若有二极管满足阳极$_n$ − 阴极$_n \geq U_{Dn}$，

则找出差值结果最大的那个二极管，

把该二极管“阳极$_n$　阴极$_n$”变成“$V_{二n} + U_{Dn}$　$V_{二n}$”，

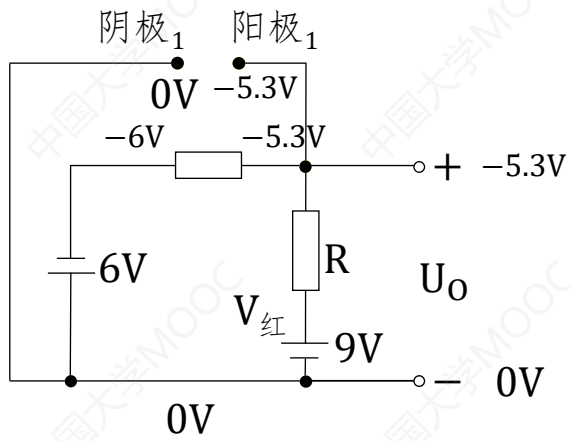


二极管2导通

二极管1截止

阳极$_1$电位 − 阴极$_1$电位 $= -5.3V - 0V = -5.3V < U_{D1} = 0.7V$

④ 分析$\mathbf{U_O}$两端的电位，输出电压$\mathbf{U_O}$＝“+”电位－“−”电位



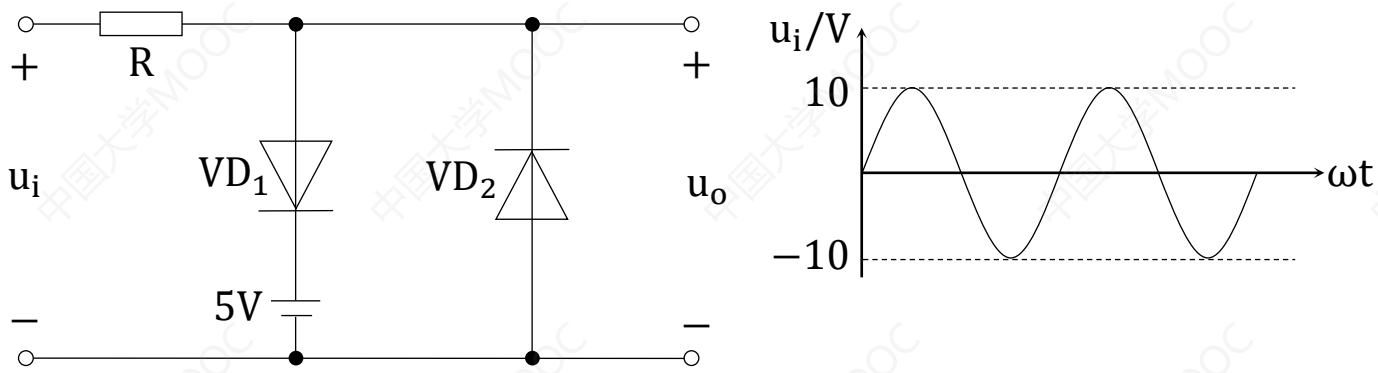
二极管2导通

二极管1截止

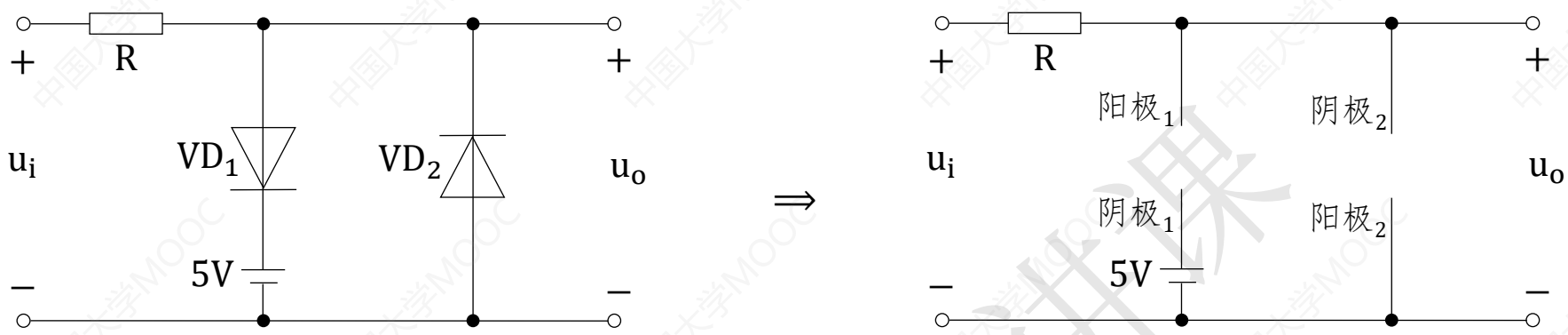
输出电压$U_O = -5.3V - 0V = -5.3V$

两个二极管画输出电压

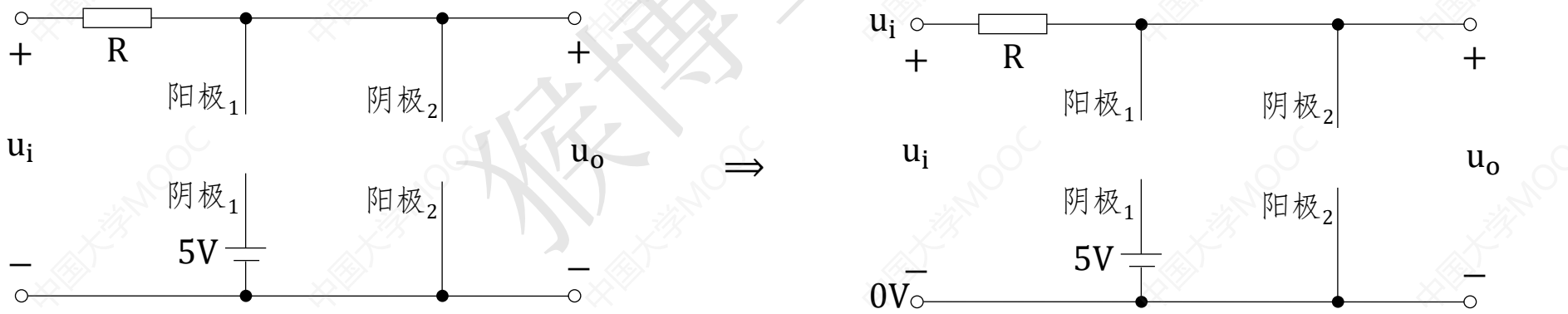
例1. 已知理想二极管电路如图所示，$U_{D1}=U_{D2}=0.7V$，试画出在 $u_i = 10\sin\omega t\ (V)$作用下输出电压 u_o的波形



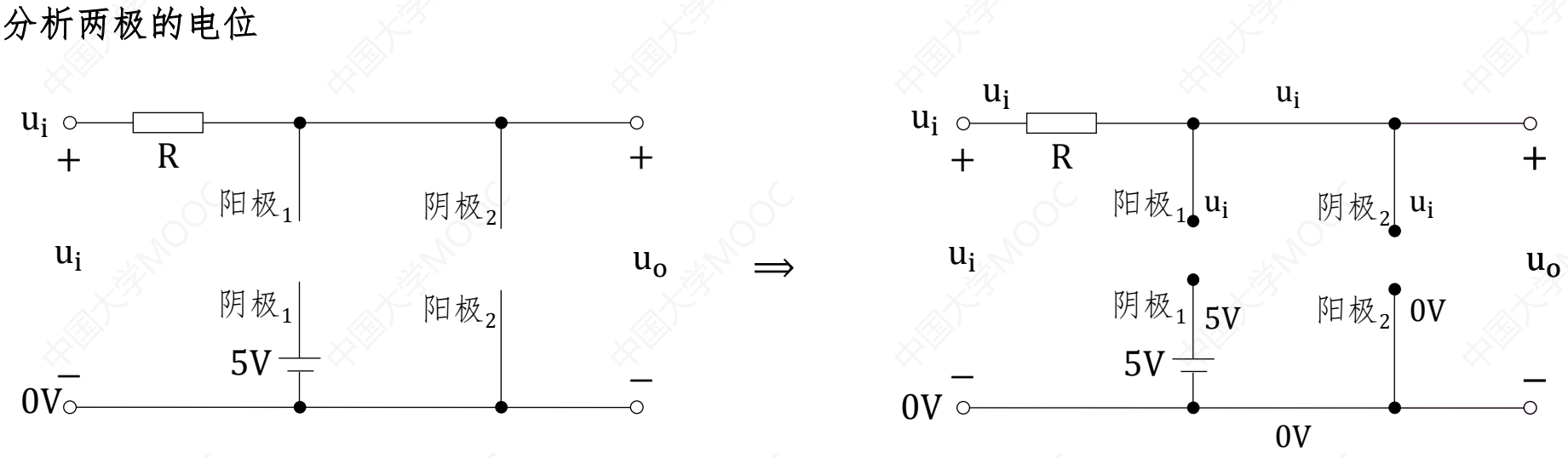
①把“⊳|”变成“阳极 阴极”
(此处断开)



②令 u_i 的“−”极电位为 0V，“+”极电位为 u_i



③分析两极的电位



④ 求 $\mathbf{u_i}$ 满足下面情况时的 $\mathbf{u_o}$ (即$\mathbf{u_o}$正极电位 − $\mathbf{u_o}$负极电位)

情况一：没有二极管满足阳极$_n$ − 阴极$_n$ ≥ $\mathbf{U_{Dn}}$，

此时正常计算 $\mathbf{u_o}$即可；

情况二：有二极管满足阳极$_n$ − 阴极$_n$ ≥ $\mathbf{U_{Dn}}$，

a、仅二极管**1**满足、二极管**2**不满足

b、仅二极管**2**满足、二极管**1**不满足

c、俩二极管均满足

c-1、二极管**1**的差更大

c-2、二极管**2**的差更大

则从中找出差值结果最大的二极管，

把“阳极$_n$　阴极$_n$”变成“$\mathbf{V_{二n}+U_{Dn}}$　$\mathbf{V_{二n}}$”

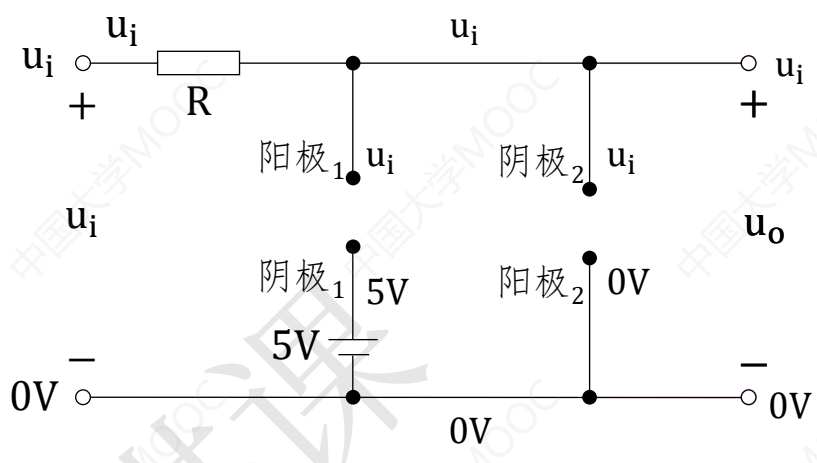
把原来分析的电位作废，再回到步骤③

情况一：

阳极$_1$ − 阴极$_1$ = u_i − 5V

阳极$_2$ − 阴极$_2$ = 0V − u_i = − u_i

$\Rightarrow$



当 $\begin{cases} u_i - 5V < 0.7V \\ -u_i < 0.7V \end{cases}$ 时，

$\Rightarrow -0.7V < u_i < 5.7V$

正常计算 u_o 即可

$u_o = u_i - 0V = u_i$

情况二：

阳极$_1$ − 阴极$_1$ = u_i − 5V

阳极$_2$ − 阴极$_2$ = 0V − u_i = − u_i

$\begin{cases} u_i - 5V \geq 0.7V \\ -u_i < 0.7V \end{cases} \Rightarrow u_i \geq 5.7V$

$\begin{cases} u_i - 5V < 0.7V \\ -u_i \geq 0.7V \end{cases} \Rightarrow u_i \leq -0.7V$

$\begin{cases} u_i - 5V \geq 0.7V \\ -u_i \geq 0.7V \end{cases} \Rightarrow u_i$ 不存在

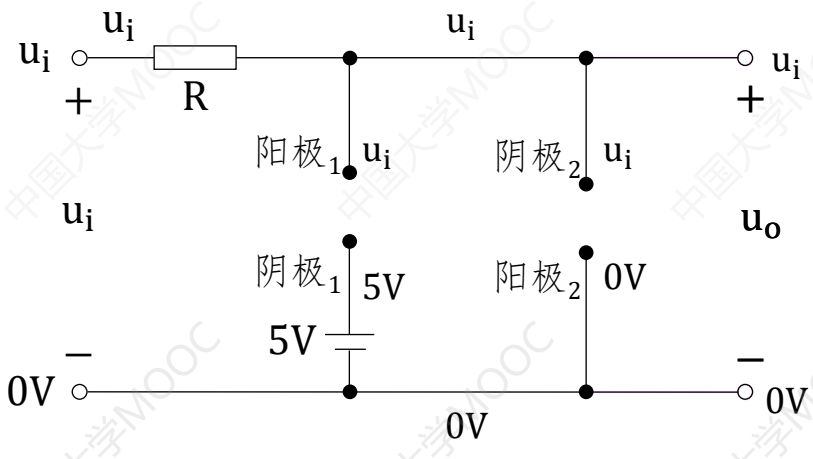
当 $u_i \geq 5.7V$ 时，情况二：

阳极$_1$ − 阴极$_1$ = u_i − 5V ≥ 0.7V

阳极$_2$ − 阴极$_2$ = 0V − u_i = − u_i ≤ − 5.7V

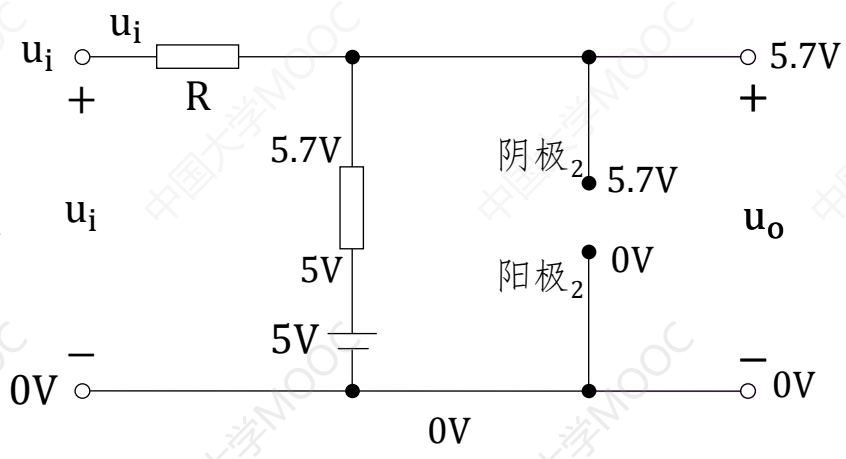
$u_o = 5.7V - 0V$

$= 5.7V$



③ 分析两极的电位

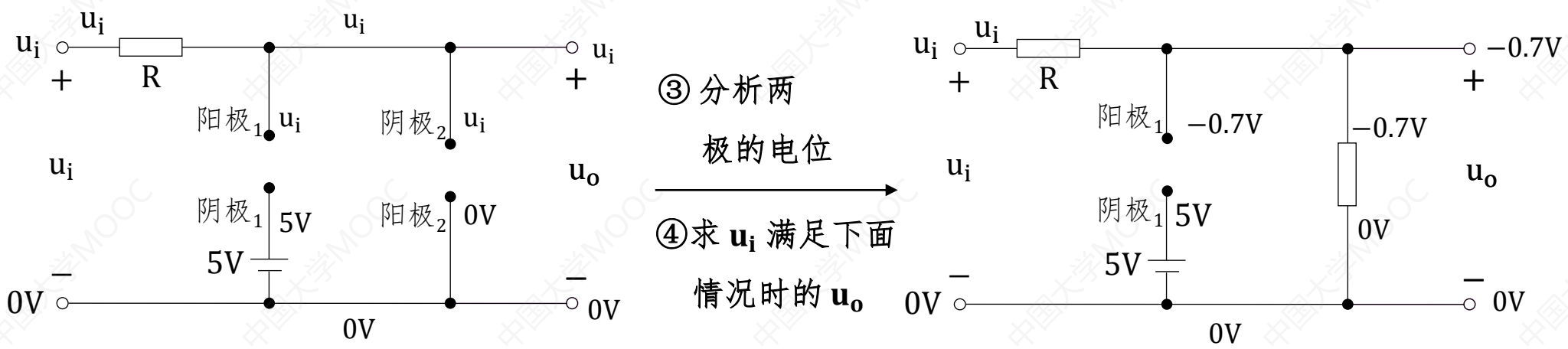
④求 $\mathbf{u_i}$ 满足下面情况时的 $\mathbf{u_o}$



当 $u_i \le -0.7V$时，情况二：

$$阳极_1 - 阴极_1 = u_i - 5V \le -5.7V$$
$$阳极_2 - 阴极_2 = 0V - u_i = -u_i \ge 0.7V$$

$$u_o = -0.7V - 0V$$
$$= -0.7V$$



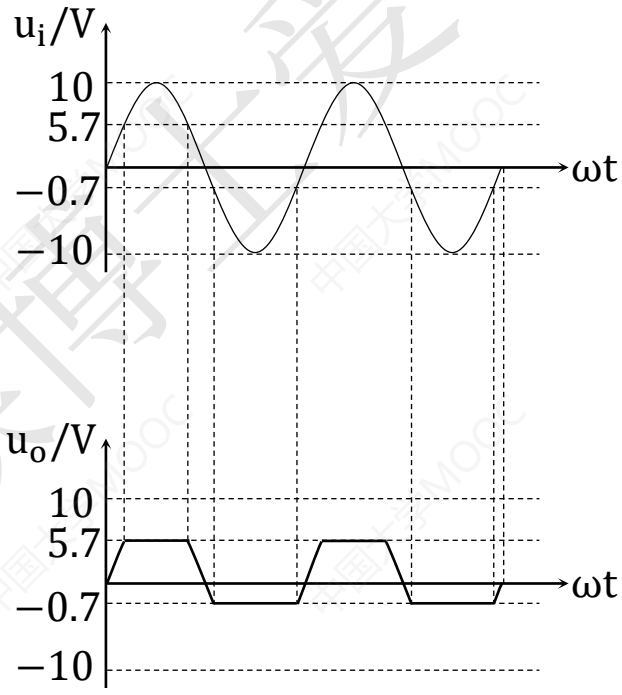
综上：

当 $-0.7V<u_i<5.7V$ 时，$u_o = u_i$

当 $u_i \ge 5.7V$ 时，$u_o = 5.7V$

当 $u_i \le -0.7V$ 时，$u_o = -0.7V$

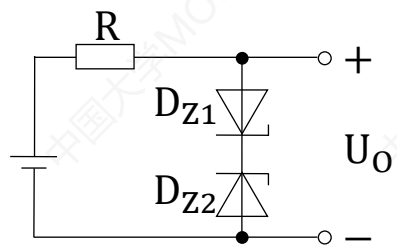
⑤ 画出 u_o 的图像



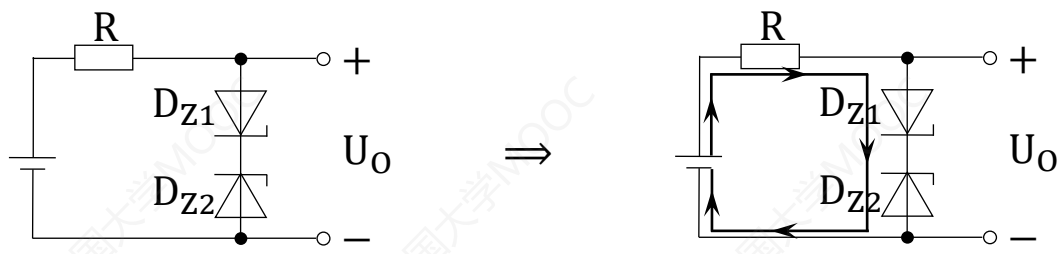
稳压二极管

例1. 已知稳压电路如图所示，U_{Z1}=4V，U_{Z2}=8V，稳压管正向导通电压 U_D 为 0.7V，则输出电压 U_O = _____

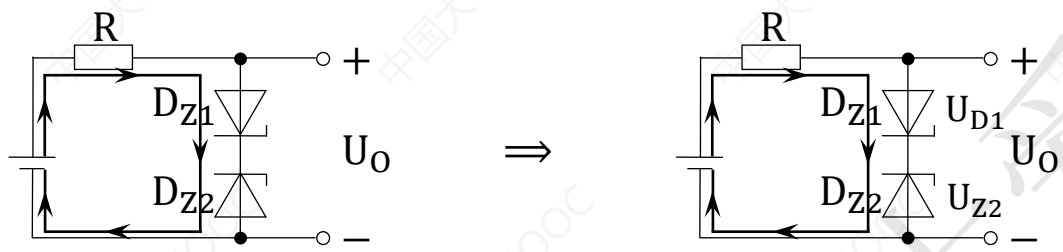
(A) 4.7V　　(B) 1.4V　　(C) 8.7V　　(D) 12V



① 从“|”长线端出发画箭头，经过“  ”，回到短线端



② 若“  ”则标 U_D，若“  ”则标 U_Z



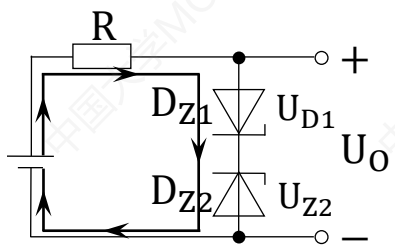
③ 若俩“  ”串联，则 U_O = 标的 U_D 或 U_Z 相加；

若俩“  ”并联，则

a、只有一个标 U_D 时，U_O = 该 U_D

b、俩都标 U_D 时，U_O = 较小那个 U_D

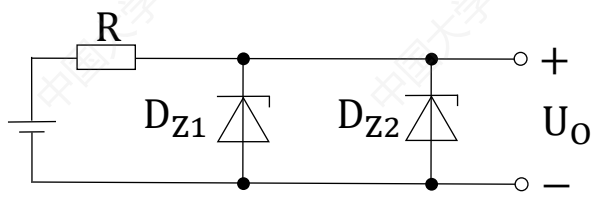
c、俩都标 U_Z 时，U_O = 较小那个 U_Z



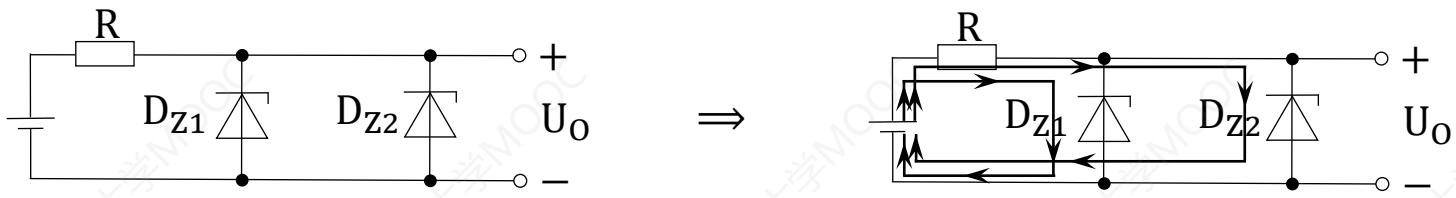
串联

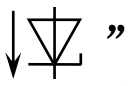
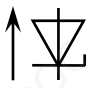
$U_O = U_{D1} + U_{Z2} = 0.7V + 8V = 8.7V$

例2. 已知稳压电路如图所示，U_{Z1}=4V，U_{Z2}=8V，稳压管正向导通电压 U_D 为 0.7V，则输出电压 U_O = ____



① 从“|”长线端出发画箭头，经过“  ”，回到短线端



② 若“  ”则标 U_D，若“  ”则标 U_Z

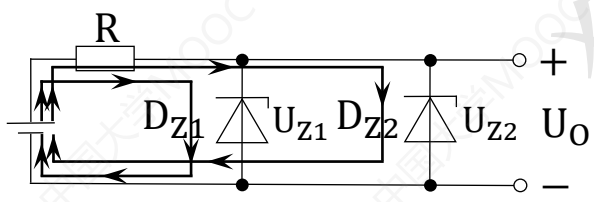
③ 若俩“  ”串联，则 U_O = 标的 U_D 或 U_Z 相加；

若俩“  ”并联，则

a、只有一个标 U_D 时， U_O = 该 U_D

b、俩都标 U_D 时， U_O = 较小那个 U_D

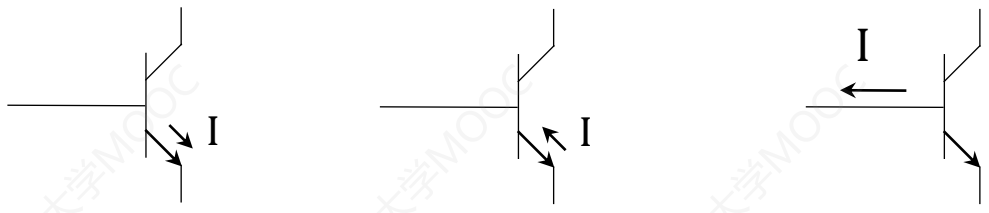
c、俩都标 U_Z 时， U_O = 较小那个 U_Z

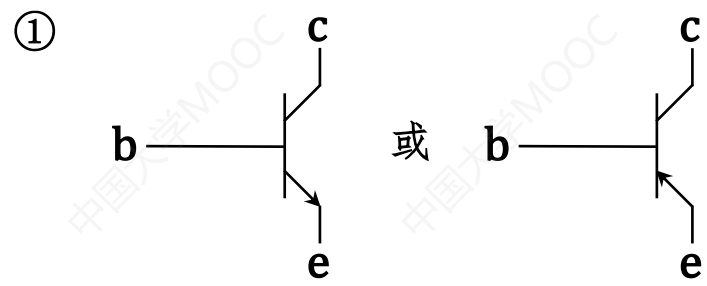


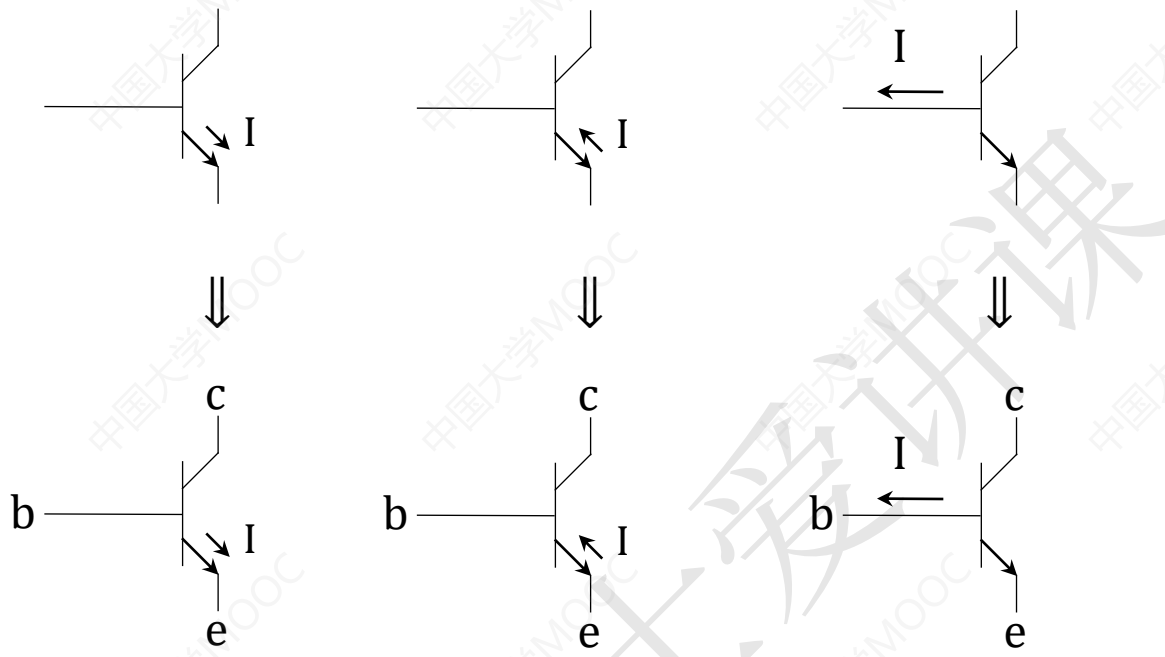
并联 $U_O = U_{Z1} = 4V$

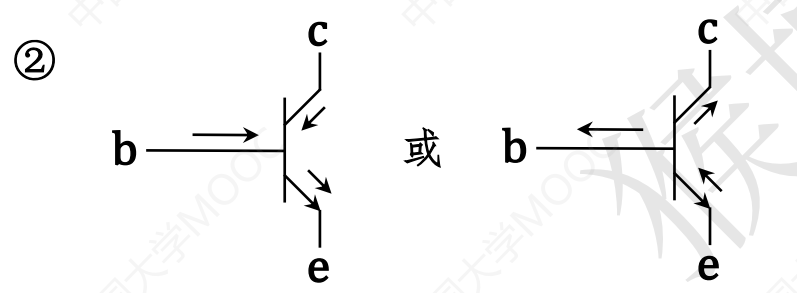
三极管的基础知识

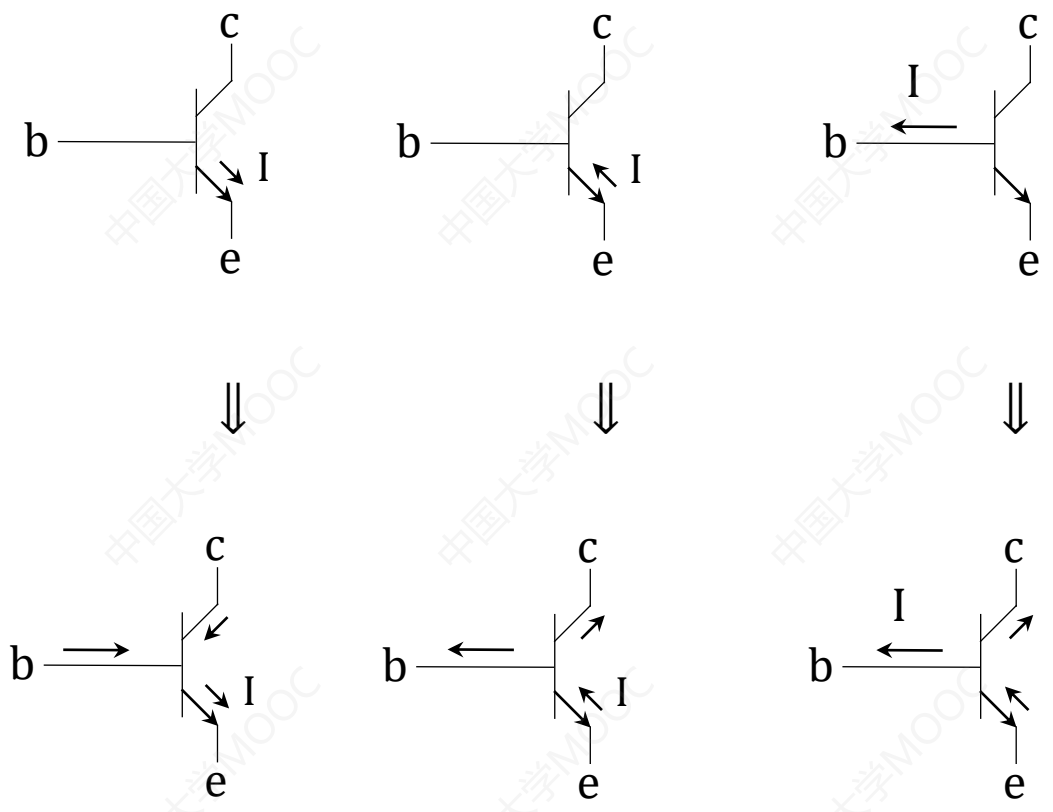
类型1. 已知几个三极管如下图所示，请确定各三极管中三极以及每一极电流的方向



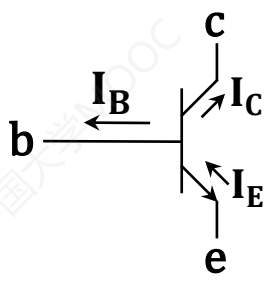


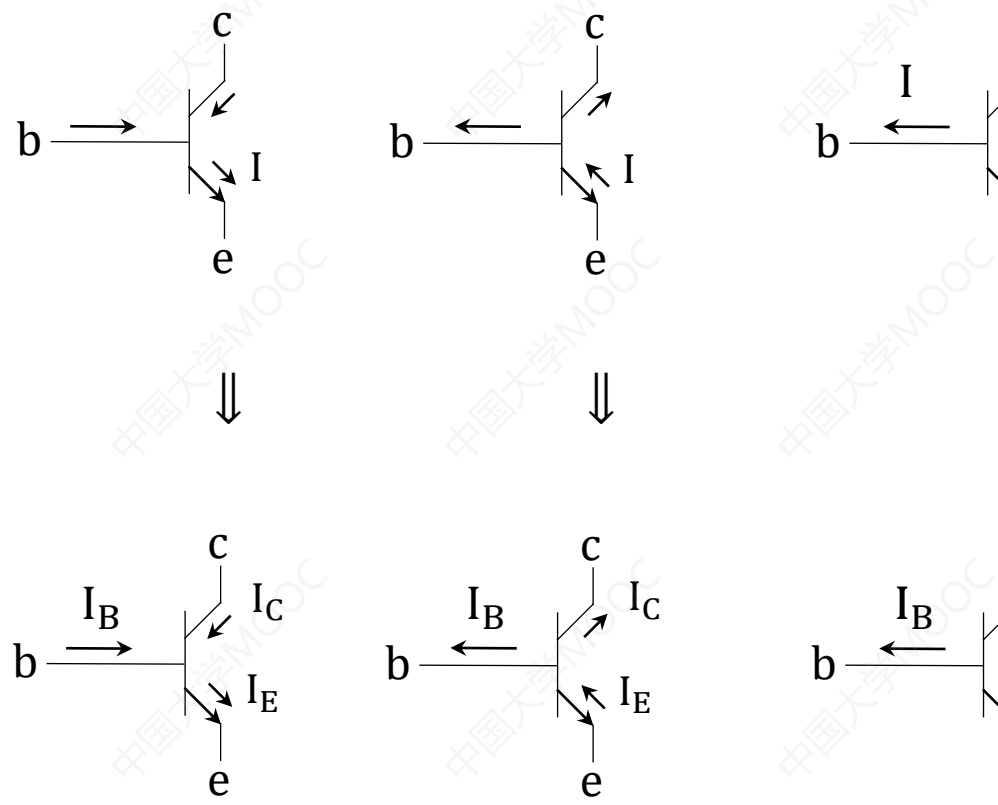






③





类型2. 已知某放大状态的三极管三个极的电位分别为2V，2.7V，4V

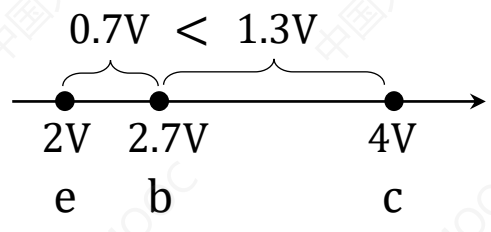
请判断该三极管的类型以及材料

① 判断题干给的三个电位分别是哪一极电位

b：三个电位中的中间值

c：剩余俩电位中离中间值较远的值

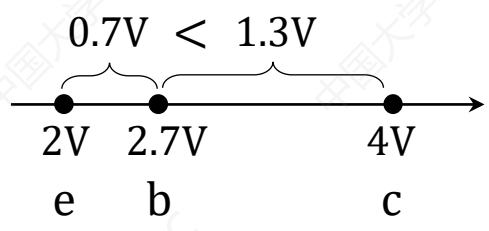
e：剩余俩电位中离中间值较近的值



② 计算 |b−e|

若结果为**0.7V**，则三极管为硅材料

若结果为**0.2V**或 **0.3V**，则三极管为锗材料



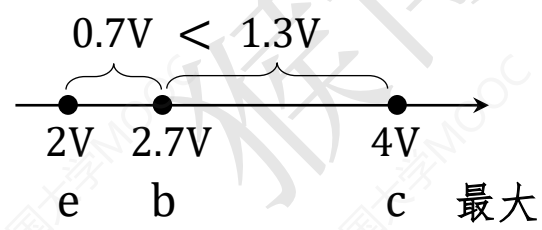
$|b-e| = |2.7V-2V| = 0.7V$

三极管为硅材料

③ 判断三极管的类型：

若 **e** 极电位值最大，为**PNP**型三极管

若 **c** 极电位值最大，为**NPN**型三极管

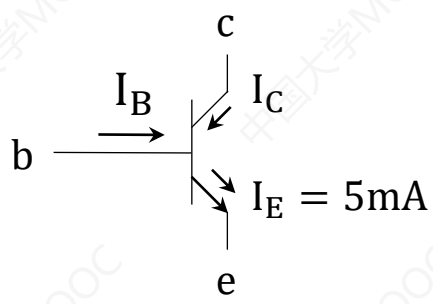


$|b-e| = |2.7V-2V| = 0.7V$

三极管为硅材料

该三极管为 NPN 型三极管

类型3. 已知某放大电路中，三极管如下图所示，其中电流放大系数 $\beta = 200$，请确定三极管未知电流两极电流的值



放大状态三极管中，bce三极电流大小的关系

$\mathbf{I_C = \beta I_B}$，$\mathbf{I_E = (1+\beta) I_B}$，$\mathbf{\beta = \frac{\Delta I_C}{\Delta I_B}}$

$$I_E = (1+\beta) I_B$$

$$\Longrightarrow 5mA = (1+200) I_B$$

$$\Longrightarrow I_B = \frac{5mA}{1+200}$$

$$\Longrightarrow I_B = \frac{5mA}{201} = 0.0249mA$$

$$I_C = \beta I_B = 200 \times 0.0249mA = 4.98mA$$

类型4. 工作在放大区的某三极管，如果 I_B 从 $12\mu A$ 增大到 $22\mu A$ 时 I_C 从 $1mA$ 增大到 $2mA$，那么它的 β 约为 ____

(A) 83　　(B) 91　　(C) 100　　(D) 200

放大状态三极管中，bce三极电流大小的关系

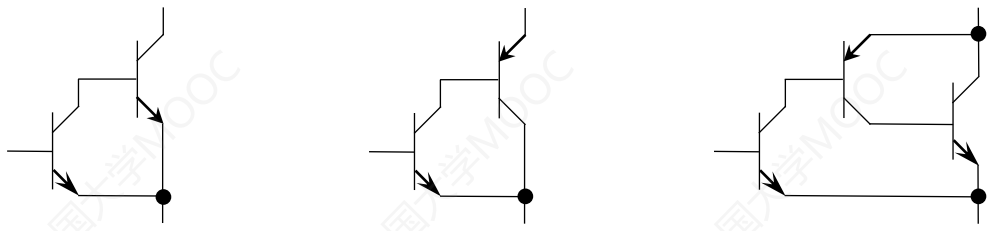
$\mathbf{I_C = \beta I_B}$，$\mathbf{I_E = (1+\beta) I_B}$，$\mathbf{\beta = \frac{\Delta I_C}{\Delta I_B}}$

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{2mA - 1mA}{22\mu A - 12\mu A} = \frac{1mA}{10\mu A} = \frac{1000\mu A}{10\mu A} = 100$$

答案：C

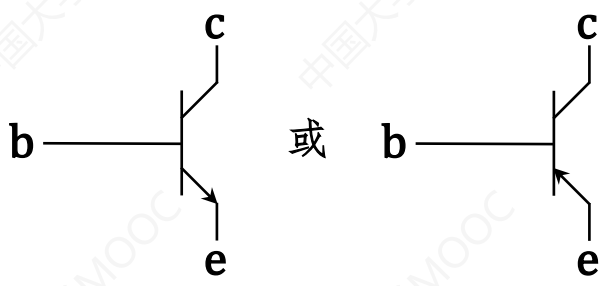
复合管

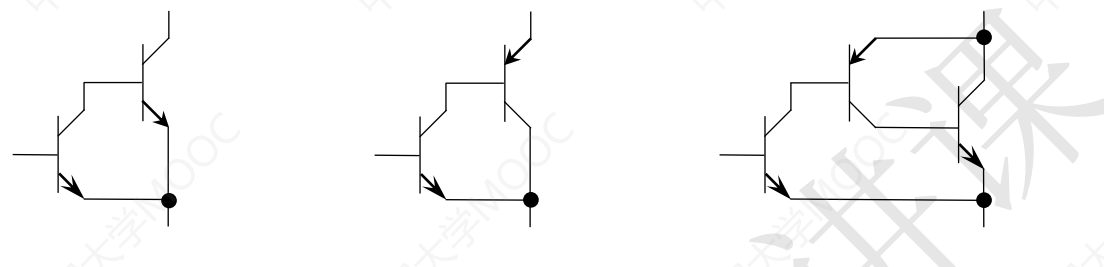
例1. 判断下面三种接法是否能构成复合管，构成复合管的等效类型(PNP型、NPN型)以及等效电极(b、c、e)



(a)　　(b)　　(c)

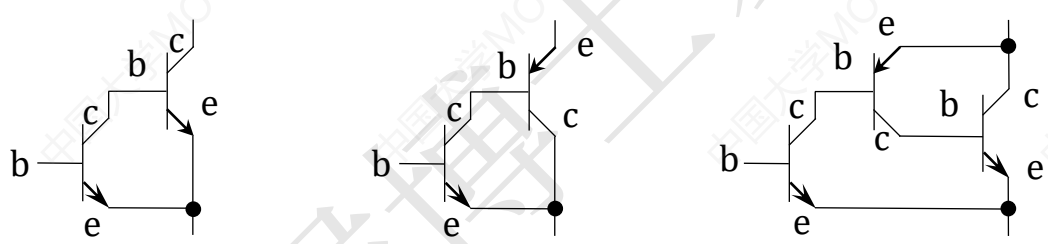
①





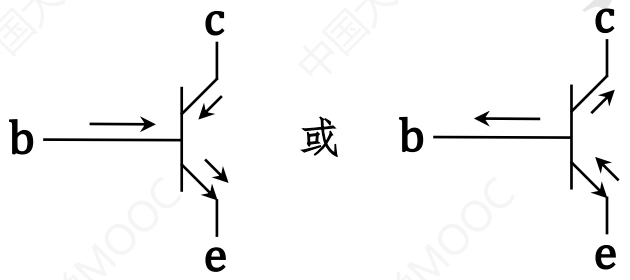
(a)　　(b)　　(c)

⇓　　⇓　　⇓



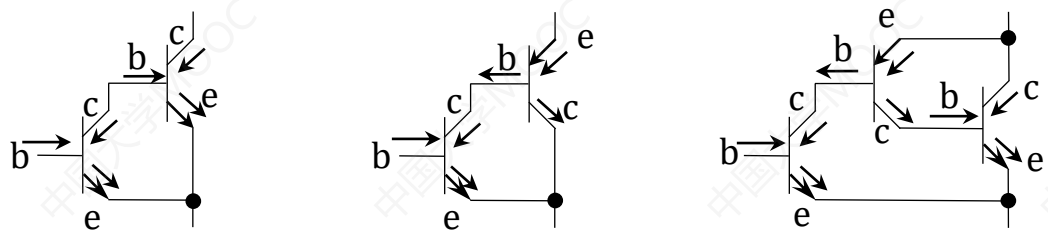
(a)　　(b)　　(c)

②



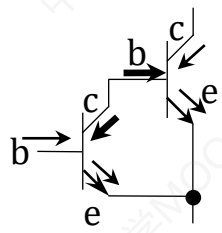
(a)　　(b)　　(c)

⇓　　⇓　　⇓



(a)　　(b)　　(c)

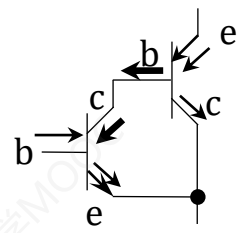
③ 观察有两条箭头的线，若箭头方向均相同则可以
构成复合管，否则，不能构成复合管



(a)

俩箭头方向不相同

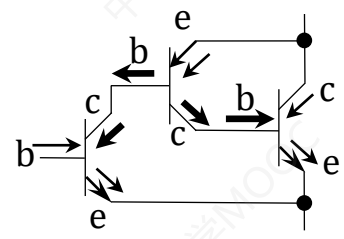
不能构成复合管



(b)

俩箭头方向相同

可以构成复合管

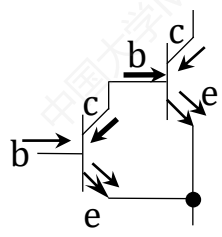


(c)

俩箭头方向相同

可以构成复合管

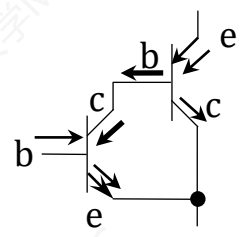
④ 最左边三极管的类型就是复合管的类型
【一入两出PNP、一出两入NPN】



(a)

俩箭头方向不相同

不能构成复合管

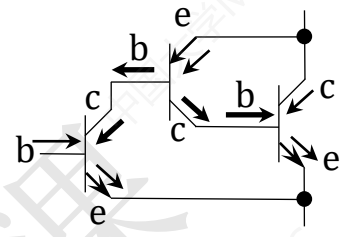


(b)

俩箭头方向相同

可以构成复合管

NPN



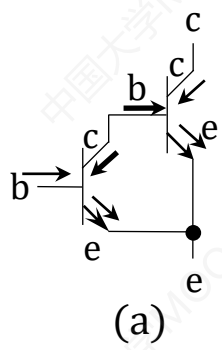
(c)

俩箭头方向相同

可以构成复合管

NPN

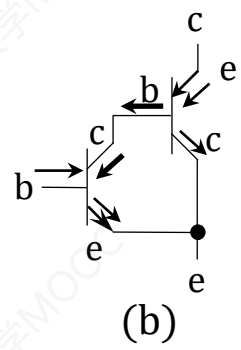
⑤ 标出复合管的三极
复合管整体里指向空气的三条线为复合管的三极
复合管三极的字母和最左边三极管一致



(a)

俩箭头方向不相同

不能构成复合管

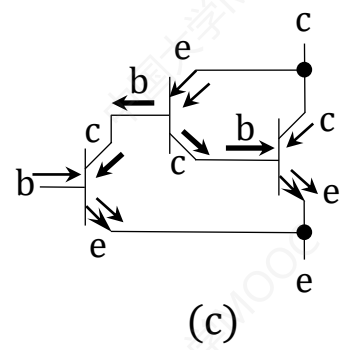


(b)

俩箭头方向相同

可以构成复合管

NPN



(c)

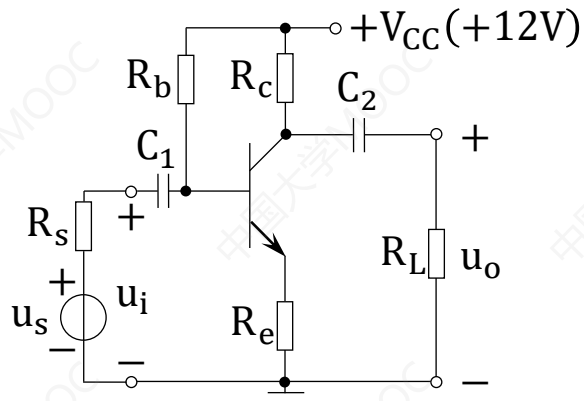
俩箭头方向相同

可以构成复合管

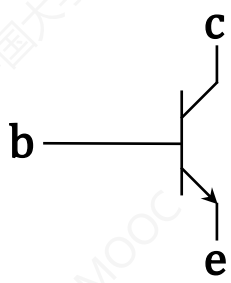
NPN

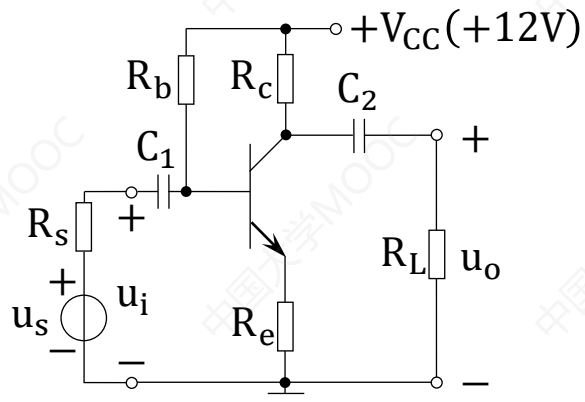
基本放大电路静态分析

例1. 已知三极管$\beta=100$，静态时$U_{BEQ}=0.7V$，$R_b=510k\Omega$，$R_c=3k\Omega$，$R_e=1k\Omega$，求静态工作点Q

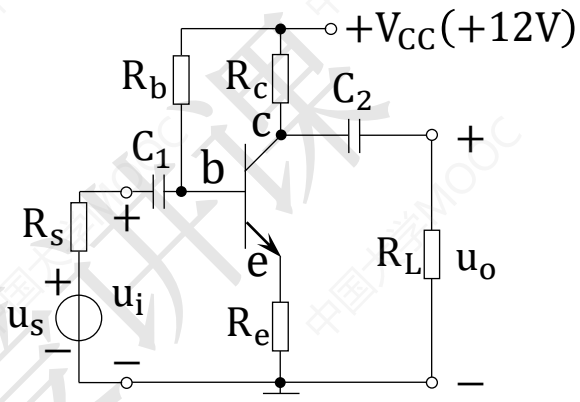


①



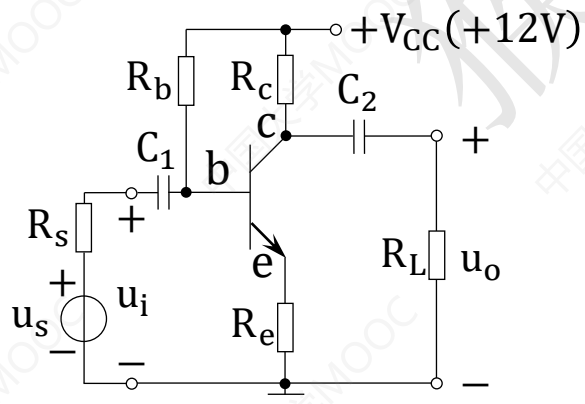


⇒

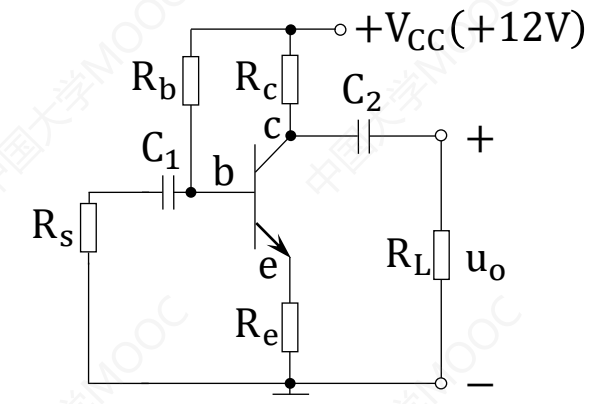


②若有“⏚”，则将“⏚”短路，并将 $\mathbf{u_i}$ 去掉

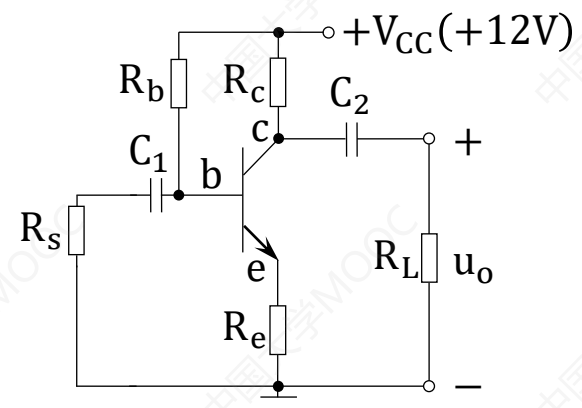
若无“⏚”，则将 $\mathbf{u_i}$ 短路



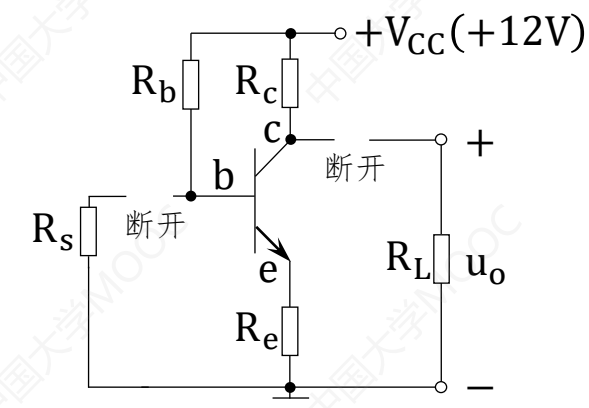
⇒



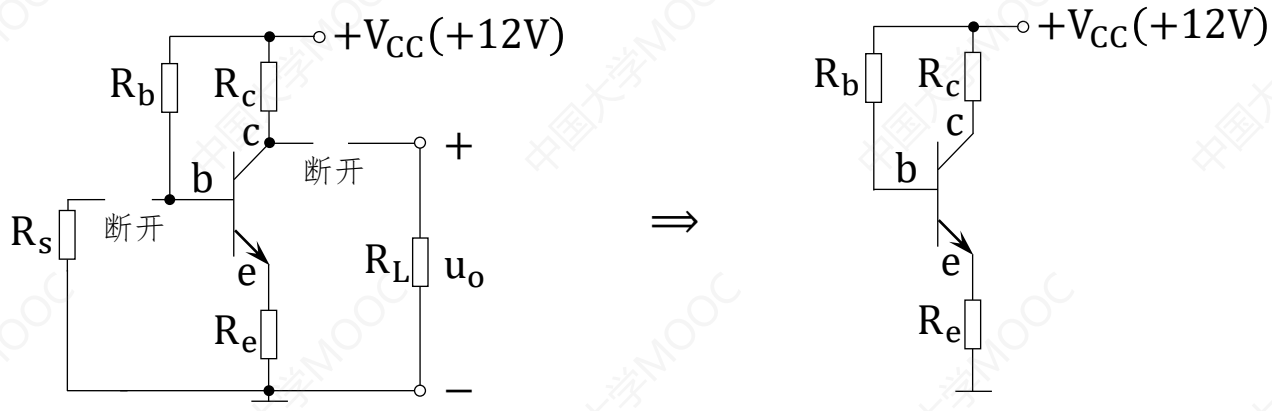
③将所有电容断开



⇒



④ 去掉电路中因为断路所以没有电流通过的部分

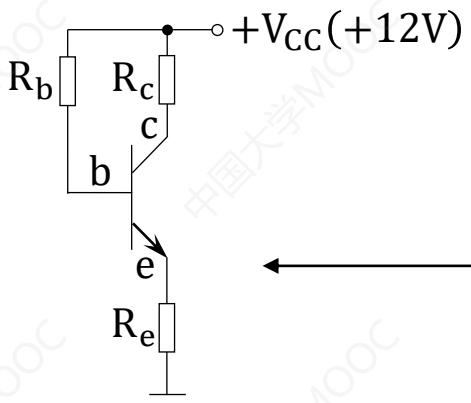


⑤ 计算 $\mathbf{I_{BQ}}$、 $\mathbf{I_{CQ}}$、 $\mathbf{U_{CEQ}}$

情况一：无电阻并在 b 极与“⊥”之间

情况二：有电阻并在 b 极与“⊥”之间，且 e 极上有电阻

情况三：有电阻并在 b 极与“⊥”之间，且 e 极上无电阻



情况一：无电阻并在 b 极与“⊥”之间

a、将 b 极与 $\mathbf{V_{CC}}$ 之间的电阻记作 $\mathbf{R_b}$， c 极上的电阻记作 $\mathbf{R_c}$， e 极上的电阻记作 $\mathbf{R_e}$

b、$\mathbf{I_{BQ}} = \frac{\mathbf{V_{CC}} - \mathbf{U_{BEQ}}}{(\mathbf{1}+\boldsymbol{\beta})\mathbf{R_e}+\mathbf{R_b}}$、$\mathbf{I_{CQ}} = \boldsymbol{\beta}\mathbf{I_{BQ}}$

$\mathbf{U_{CEQ}} = \mathbf{V_{CC}} - \mathbf{I_{CQ}} \cdot \mathbf{R_c} - (\mathbf{1} + \boldsymbol{\beta})\mathbf{I_{BQ}} \cdot \mathbf{R_e}$

$R_b = 510k\Omega$

$R_c = 3k\Omega$

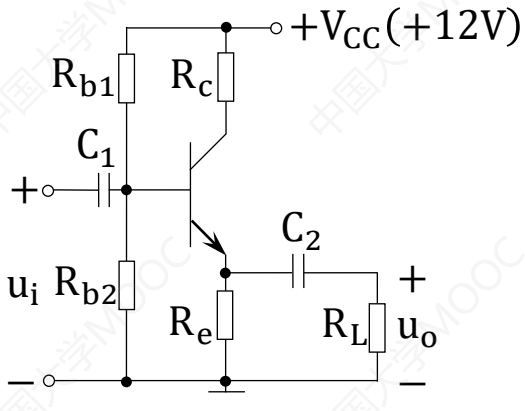
$R_e = 1k\Omega$

$$I_{BQ} = \frac{V_{CC} - U_{BEQ}}{(1+\beta)R_e+R_b} = \frac{12V - 0.7V}{(1+100)\times 1k\Omega+510k\Omega} = 0.0185mA$$

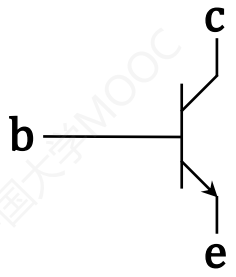
$$I_{CQ} = \beta I_{BQ} = 100 \times 0.0185mA = 1.85mA$$

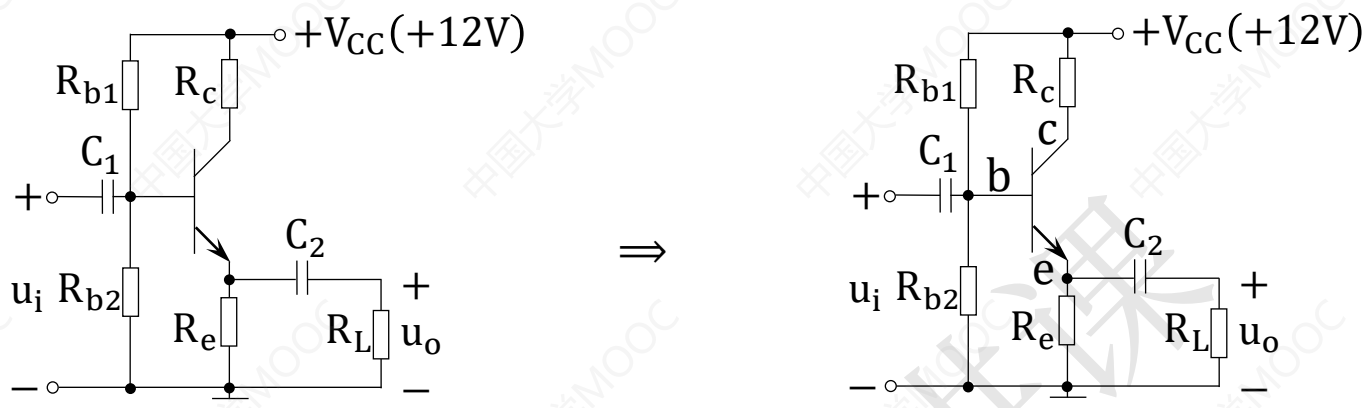
$$U_{CEQ} = V_{CC} - I_{CQ} \cdot R_c - (1+\beta)I_{BQ} \cdot R_e = 12V - 1.85mA \times 3k\Omega - (1+100) \times 0.0185mA \times 1k\Omega = 4.5815V$$

例2. 已知三极管β=30，R_{b1}=7.5kΩ，R_{b2}=2.5kΩ，R_L=2kΩ，R_e=1kΩ，R_c=2kΩ，静态时U_{BEQ}=0.7V，求静态工作点Q



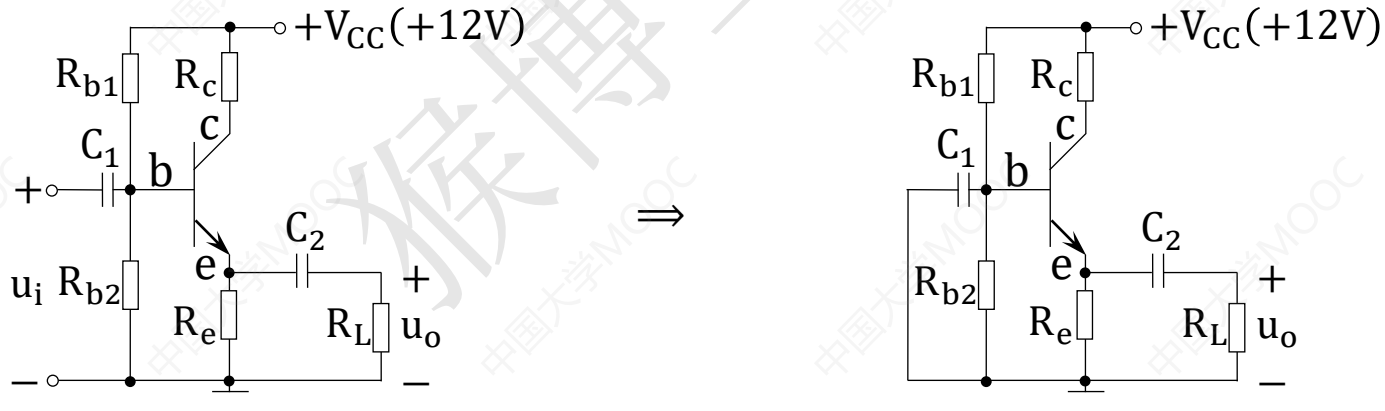
①



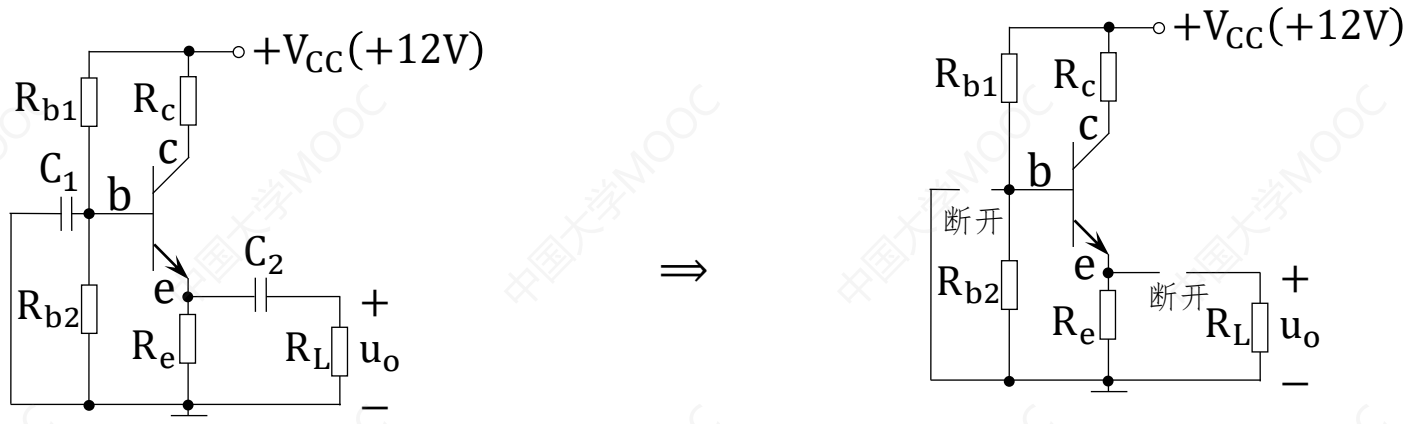


② 若有“⏀”，则将“⏀”短路，并将 u_i 去掉

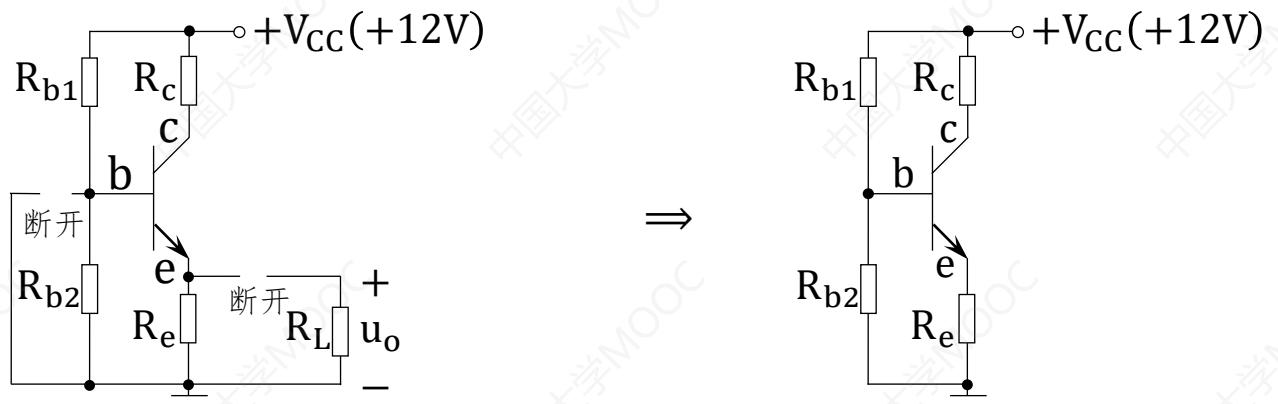
若无“⏀”，则将 u_i 短路



③ 将所有电容断开



④ 去掉电路中因为断路所以没有电流通过的部分

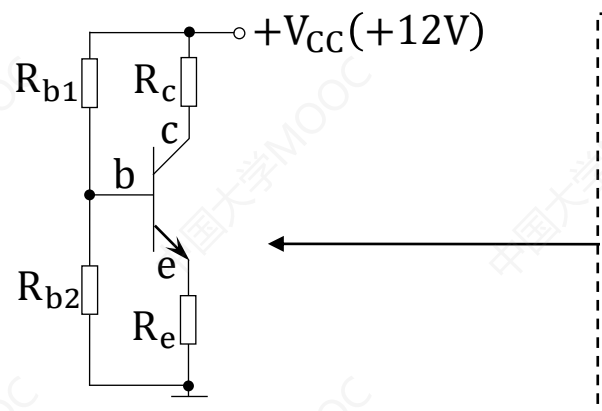


⑤ 计算 $\mathbf{I_{BQ}}$、$\mathbf{I_{CQ}}$、$\mathbf{U_{CEQ}}$

情况一：无电阻并在 b 极与“⊥”之间

情况二：有电阻并在 b 极与“⊥”之间，且 e 极上有电阻

情况三：有电阻并在 b 极与“⊥”之间，且 e 极上无电阻



情况二：有电阻并在 b 极与“⊥”之间，且 e 极上有电阻

a、将 b 极与 $\mathbf{V_{CC}}$ 之间的电阻记作 $\mathbf{R_{b1}}$，b 极与“⊥”之间的电阻记作 $\mathbf{R_{b2}}$，c 极上的电阻记作 $\mathbf{R_c}$，e 极上的电阻记作 $\mathbf{R_e}$

b、$\mathbf{I_{BQ}=\frac{1}{(1+\beta)R_e}\cdot(\frac{R_{b2}}{R_{b1}+R_{b2}}V_{CC}-U_{BEQ})}$、$\mathbf{I_{CQ}=\beta I_{BQ}}$

$\mathbf{U_{CEQ}=V_{CC}-I_{CQ}\cdot R_c-(1+\beta)I_{BQ}\cdot R_e}$

$R_{b1}=7.5k\Omega$

$R_{b2}=2.5k\Omega$

$R_c=2k\Omega$

$R_e=1k\Omega$

$$I_{BQ}=\frac{1}{(1+\beta)R_e}\cdot(\frac{R_{b2}}{R_{b1}+R_{b2}}V_{CC}-U_{BEQ})$$

$$=\frac{1}{(1+30)\times 1k\Omega}\times(\frac{2.5k\Omega}{7.5k\Omega+2.5k\Omega}\times 12V-0.7V)$$

$$=0.074mA$$

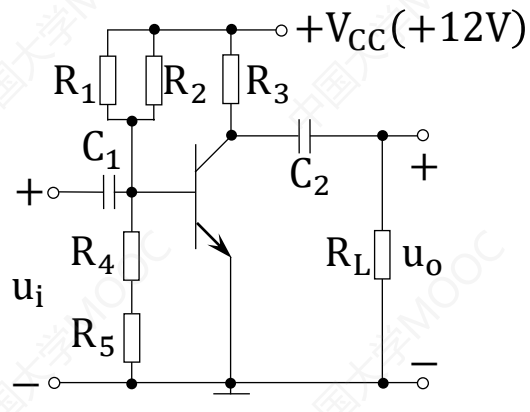
$$I_{CQ}=\beta I_{BQ}=30\times 0.074mA=2.22mA$$

$$U_{CEQ}=V_{CC}-I_{CQ}\cdot R_c-(1+\beta)I_{BQ}\cdot R_e$$

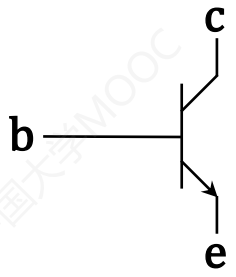
$$=12V-2.22mA\times 2k\Omega-(1+30)\times 0.074mA\times 1k\Omega$$

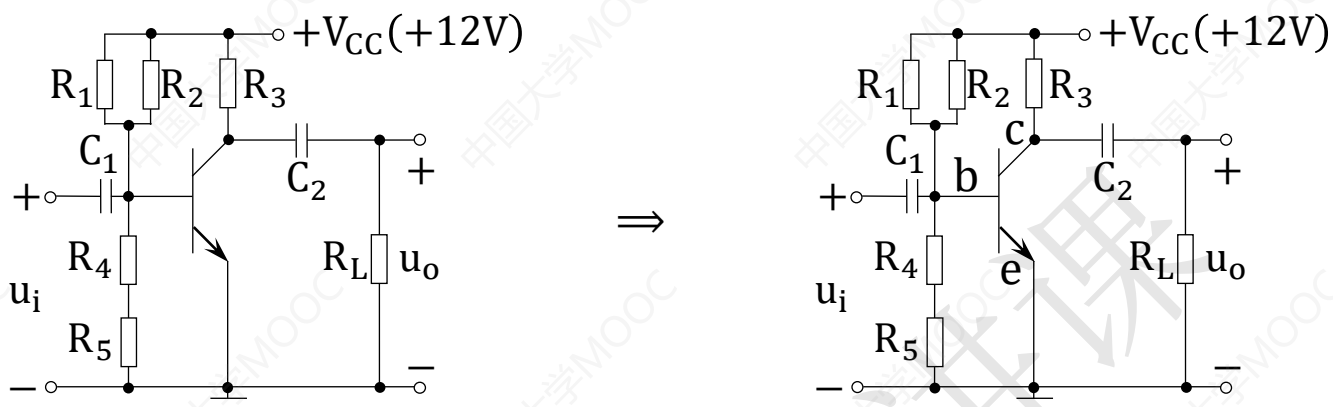
$$=5.266V$$

例3. 已知三极管$\beta=100$，$R_1=112k\Omega$，$R_2=112k\Omega$，$R_3=5k\Omega$，$R_L=5k\Omega$，$R_4=2k\Omega$，$R_5=1.8k\Omega$，静态时$U_{BEQ}=0.7V$，求静态工作点Q



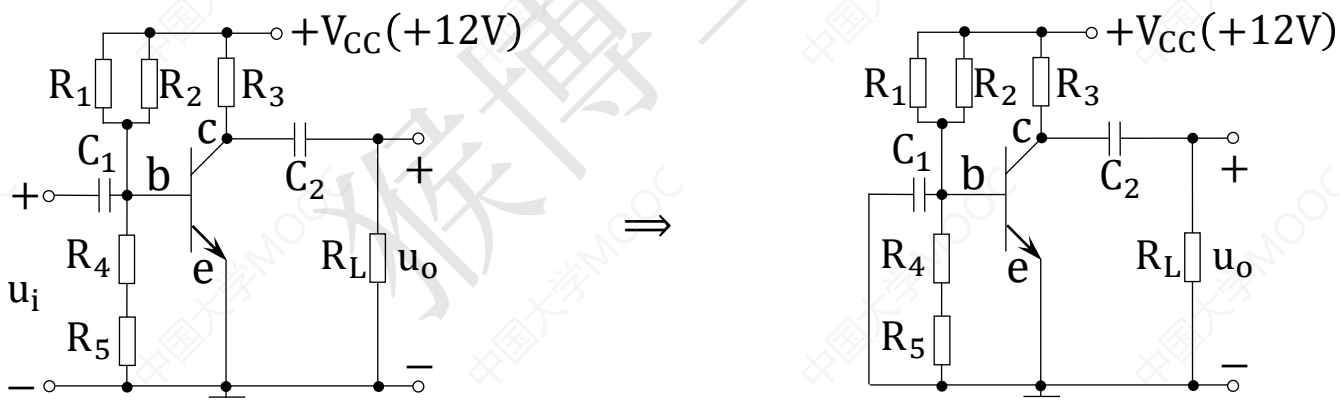
①



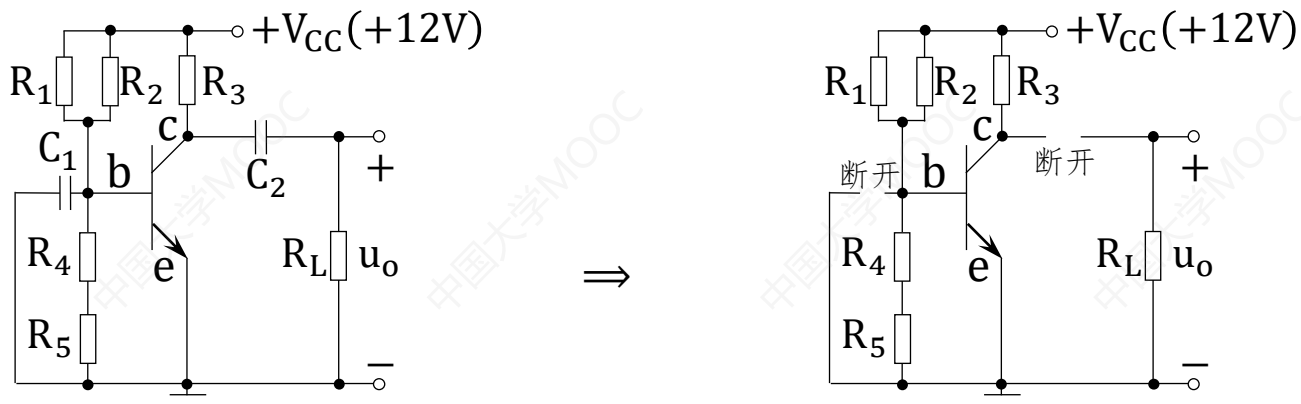


②若有“⏀”，则将“⏀”短路，并将 $\mathbf{u_i}$ 去掉

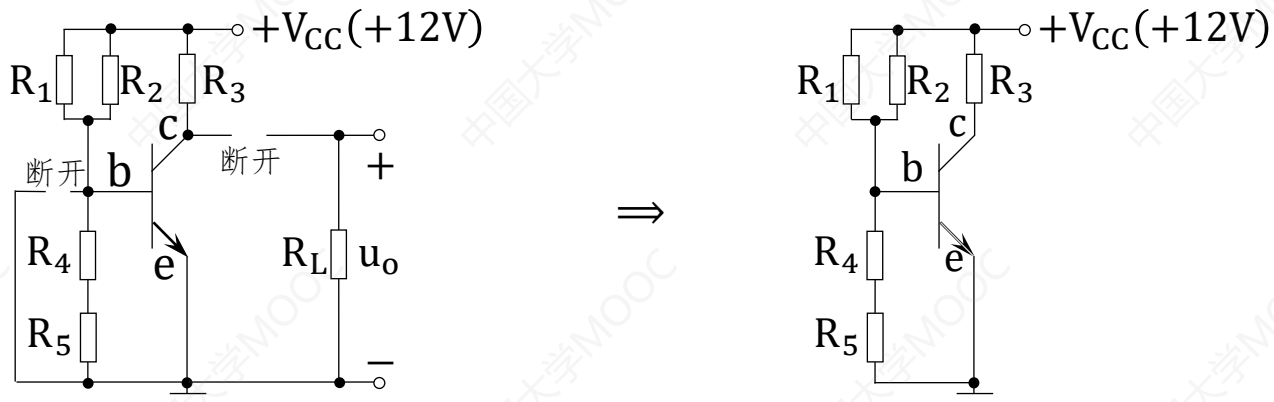
若无“⏀”，则将 $\mathbf{u_i}$ 短路



③将所有电容断开



④ 去掉电路中因为断路所以没有电流通过的部分

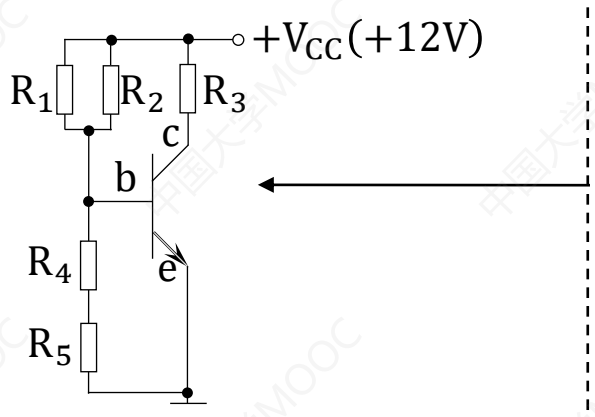


⑤ 计算 $\mathbf{I_{BQ}}$、$\mathbf{I_{CQ}}$、$\mathbf{U_{CEQ}}$

情况一：无电阻并在 b 极与“⊥”之间

情况二：有电阻并在 b 极与“⊥”之间，且 e 极上有电阻

情况三：有电阻并在 b 极与“⊥”之间，且 e 极上无电阻



情况三：有电阻并在 b 极与“⊥”之间，且 e 极上无电阻

a、将 b 极与 $\mathbf{V_{CC}}$ 之间的电阻记作 $\mathbf{R_{b1}}$，b 极与“⊥”之间的电阻记作 $\mathbf{R_{b2}}$，c 极上的电阻记作 $\mathbf{R_c}$

b、$\mathbf{I_{BQ}} = \frac{\mathbf{V_{CC}} - \mathbf{U_{BEQ}}}{\mathbf{R_{b1}}} - \frac{\mathbf{U_{BEQ}}}{\mathbf{R_{b2}}}$、$\mathbf{I_{CQ}} = \boldsymbol{\beta}\mathbf{I_{BQ}}$

$\mathbf{U_{CEQ}} = \mathbf{V_{CC}} - \mathbf{I_{CQ}} \cdot \mathbf{R_c}$

$$R_{b1} = R_1 // R_2 = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{112k\Omega \times 112k\Omega}{112k\Omega + 112k\Omega} = 56k\Omega$$

$$R_{b2} = R_4 + R_5 = 2k\Omega + 1.8k\Omega = 3.8k\Omega$$

$$R_c = R_3 = 5k\Omega$$

$$I_{BQ} = \frac{V_{CC} - U_{BEQ}}{R_{b1}} - \frac{U_{BEQ}}{R_{b2}} = \frac{12V - 0.7V}{56k\Omega} - \frac{0.7V}{3.8k\Omega} = 0.0176mA$$

$$I_{CQ} = \beta I_{BQ} = 100 \times 0.0176mA = 1.76mA$$

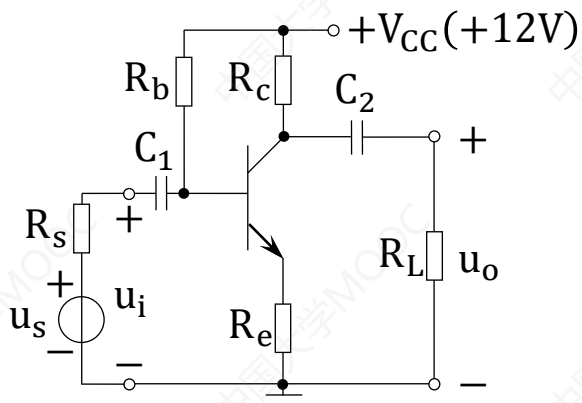
$$U_{CEQ} = V_{CC} - I_{CQ} \cdot R_c = 12V - 1.76mA \times 5k\Omega = 3.2V$$

共发射极放大电路的动态分析

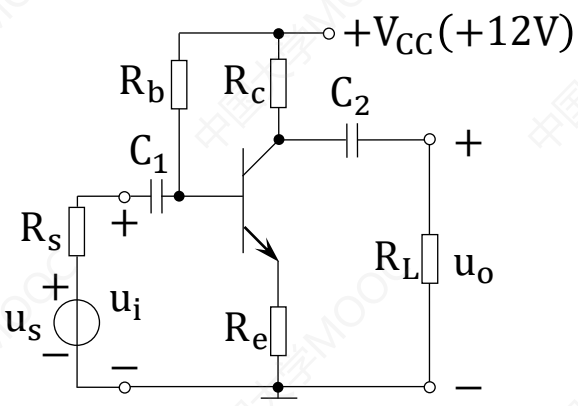
例1. 已知三极管$\beta=100$，$r'_{bb}=95\Omega$，静态时$U_{BEQ}=0.7V$，$R_b=510k\Omega$，$R_c=3k\Omega$，$R_L=3k\Omega$，$R_e=1k\Omega$，求：

(1) 求$\dot{A}_u$、R_i、R_o

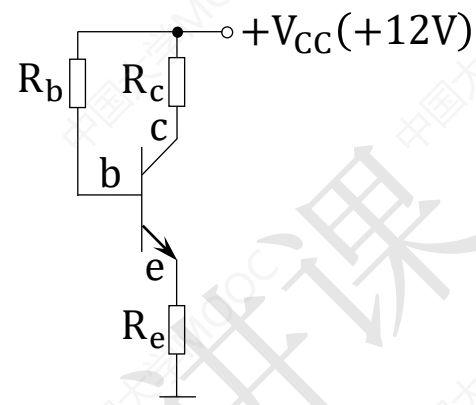
(2) 求最大不失真输出电压幅值U_{omax}



一、静态分析



$\Rightarrow$



$R_b=510k\Omega$

$R_c=3k\Omega$

$R_e=1k\Omega$

$$I_{BQ}=\frac{V_{CC}-U_{BEQ}}{(1+\beta)R_e+R_b}$$

$$=\frac{12V-0.7V}{(1+100)\times 1k\Omega+510k\Omega}$$

$$=0.0185mA$$

$$I_{CQ}=\beta I_{BQ}=100\times 0.0185mA=1.85mA$$

$$U_{CEQ}=V_{CC}-I_{CQ}\cdot R_c-(1+\beta)I_{BQ}\cdot R_e$$

$$=12V-1.85mA\times 3k\Omega-(1+100)\times 0.0185mA\times 1k\Omega$$

$$=4.5815V$$

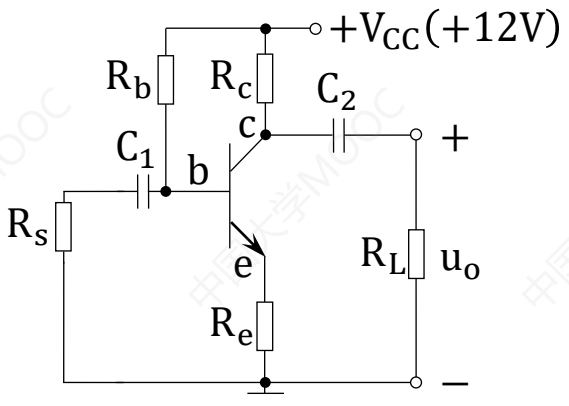
详见【基本放大电路】第1课【基本放大电路静态分析】

二、动态分析

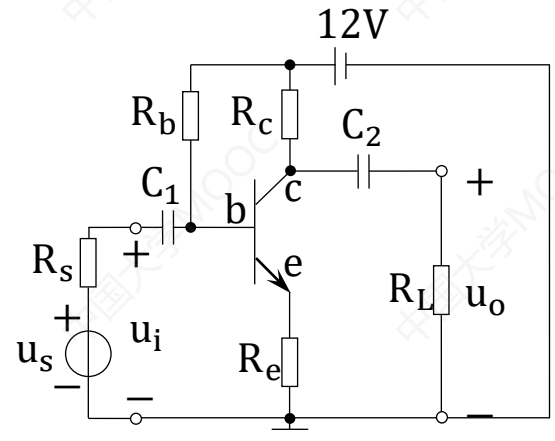
① 画微变等效电路

a、将“ −?V ”变成“ ?V ”

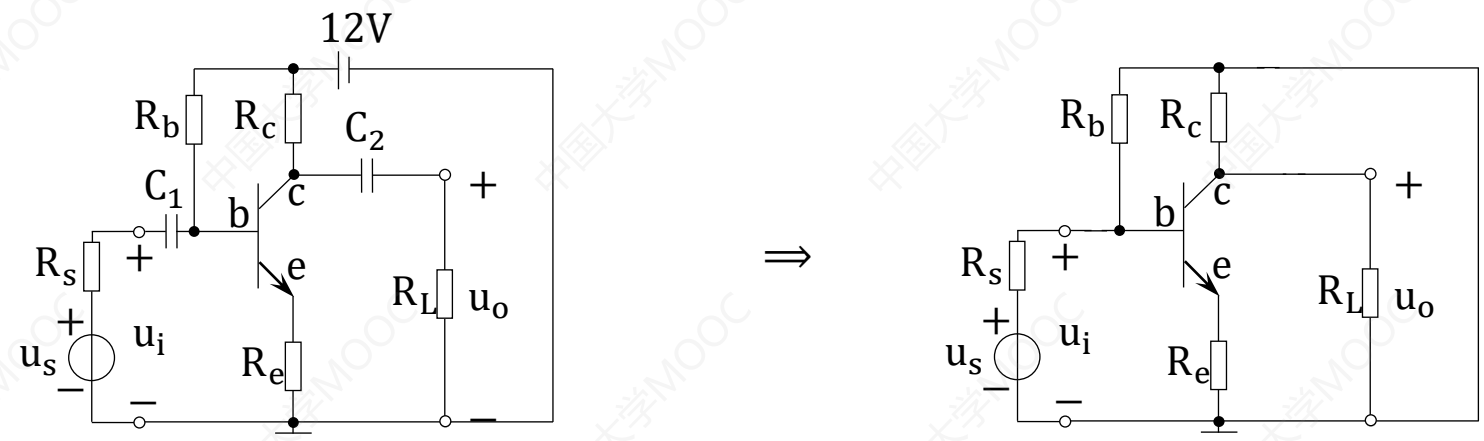
将“ +?V ”变成“ ?V ”

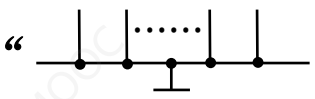


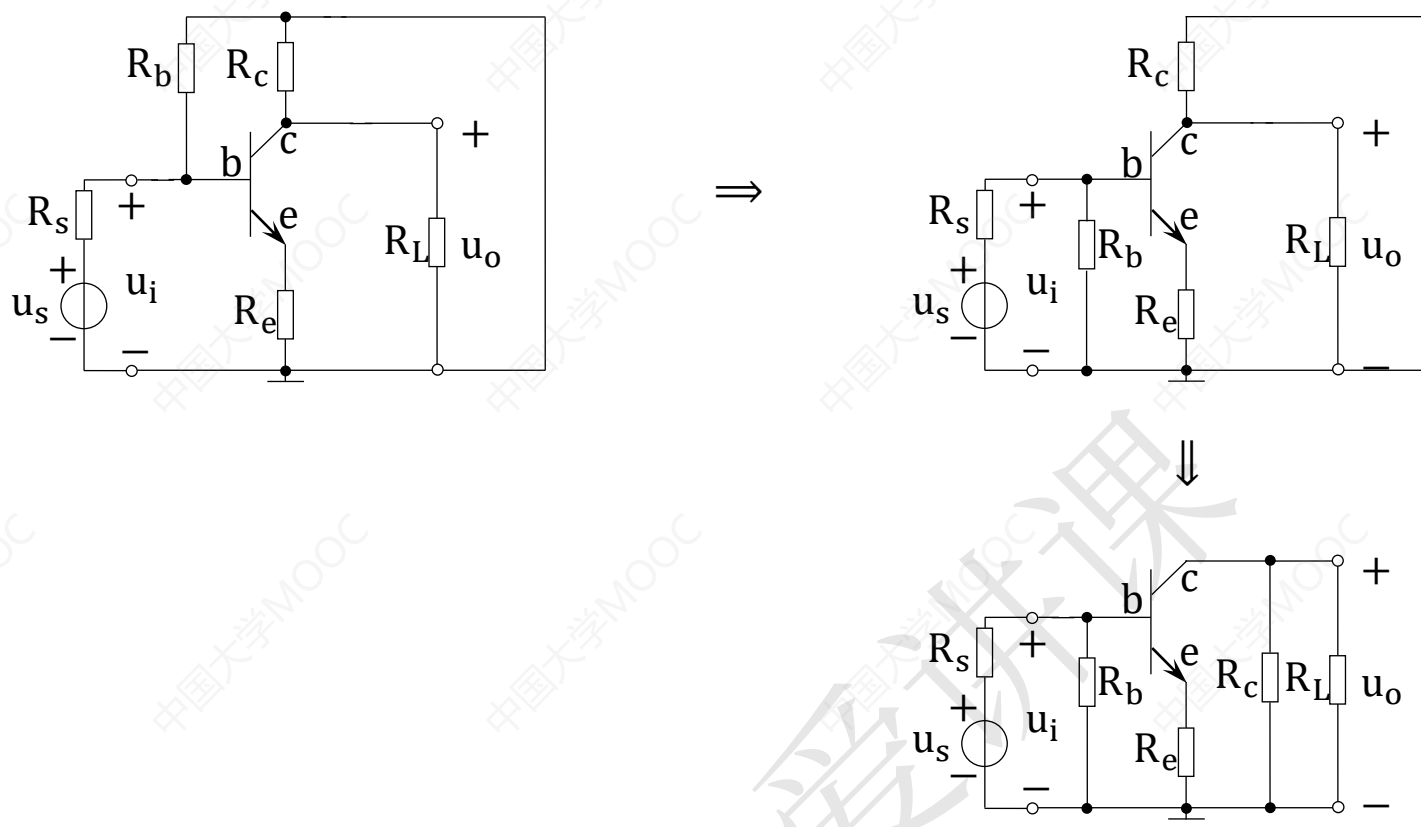
$\Rightarrow$

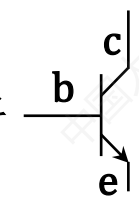


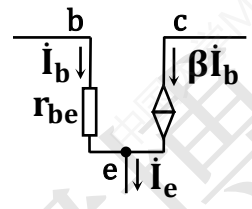
b、将电容与直流电源短路



c、让同“⊥”相连的线都变成“  ”

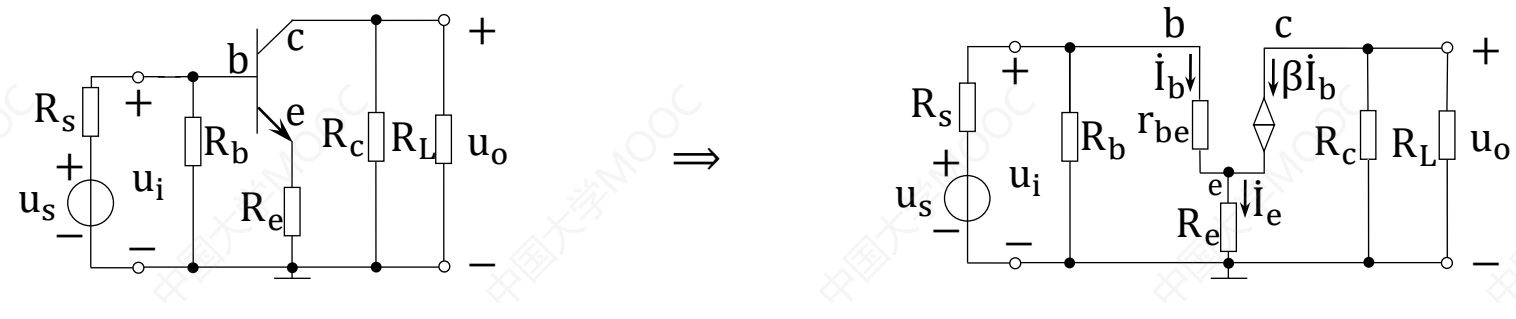


d、将 

变成 

其中$r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{BQ}+I_{CQ}}$

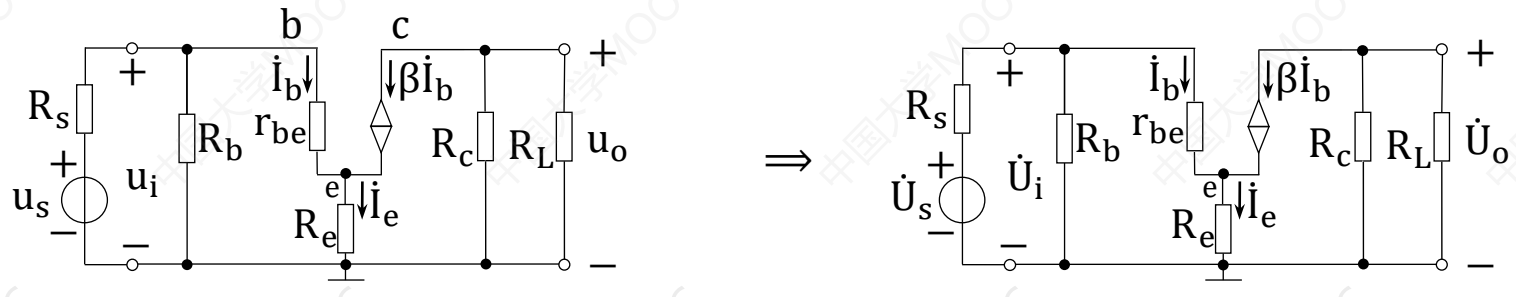
【若题干没有给出r'_{bb}，则默认$r'_{bb} = 200\Omega$】



$$r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{BQ}+I_{CQ}}$$

$$= 95\Omega + (1+100)\times\frac{26mV}{0.0185mA + 1.85mA} = 95\Omega + 101\times\frac{26\times10^{-3}V}{1.8685\times10^{-3}A} = 1500\Omega = 1.5k\Omega$$

e、将图中所有 $u_{啥}$ 变成 $\dot{U}_{啥}$



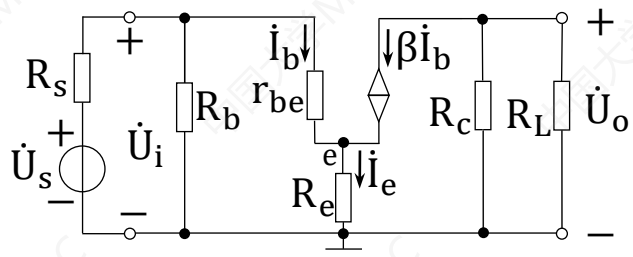
② 求几个等效电阻

a、将三极管 **b** 极与 $\dot{U}_i$ 之间的电阻等效成电阻 R'_b

b、将三极管 **e** 极与“⊥”之间的电阻等效成电阻 R'_e

c、将三极管外 **c** 极侧的电阻等效为电阻 R'_c

d、将三极管与 R_L 之间的电阻等效成电阻 R'_o



(1) $I_{BQ}= 0.0185mA \quad I_{CQ} =1.85mA$

$U_{CEQ} = 4.5815V$

$r_{be} = 1.5k\Omega$

$R'_b = R_b = 510k\Omega$

$R'_e = R_e = 1k\Omega$

$R'_c = R_c // R_L$

$= \frac{R_c \cdot R_L}{R_c + R_L}$

$= \frac{3k\Omega \cdot 3k\Omega}{3k\Omega + 3k\Omega}$

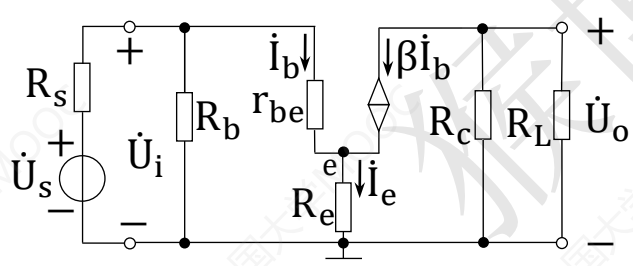
$= 1.5k\Omega$

$R'_o = R_c = 3k\Omega$

③ $\dot{A}_u = -\frac{\beta R'_c}{r_{be}+(1+\beta)R'_e}$

$R_i = R'_b // [r_{be} + (1+\beta)R'_e]$

$R_o = R'_o$



(1) $I_{BQ}= 0.0185mA \quad I_{CQ} =1.85mA$

$U_{CEQ} = 4.5815V$

$r_{be} = 1.5k\Omega$

$R'_b = 510k\Omega \qquad R'_c = 1.5k\Omega$

$R'_e = 1k\Omega \qquad R'_o = 3k\Omega$

$\dot{A}_u = -\frac{\beta R'_c}{r_{be}+(1+\beta)R'_e}$

$= -\frac{100\times 1.5k\Omega}{1.5k\Omega+(1+100)\times 1k\Omega}$

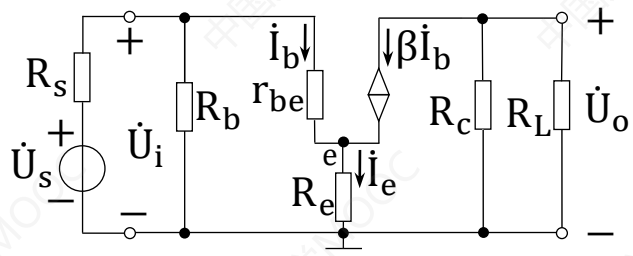
$= -1.46$

$R_i = R'_b // [r_{be} + (1+\beta)R'_e] = \frac{R'_b \cdot [r_{be}+(1+\beta)R'_e]}{R'_b + [r_{be}+(1+\beta)R'_e]} = \frac{510k\Omega \times [1.5k\Omega + (1+100)\times 1k\Omega]}{510k\Omega + [1.5k\Omega + (1+100)\times 1k\Omega]} = 85.3k\Omega$

$R_o = R'_o = 3k\Omega$

④ $\mathbf{U_{omax} = min\{ U_{CEQ} - U_{CES}，\ I_{CQ}R'_c \}}$

$\mathbf{U_{CES}}$ 题干会给，若没给则 $\mathbf{U_{CES} = U_{BEQ}}$



(1) I_{BQ}= 0.0185mA　I_{CQ} =1.85mA

$U_{CEQ} = 4.5815V$

$r_{be} = 1.5k\Omega$

$R'_b = 510k\Omega$　　$R'_c = 1.5k\Omega$

$R'_e = 1k\Omega$　　$R'_o = 3k\Omega$

$\dot{A}_u = -1.46$　　$R_i = 85.3k\Omega$

$R_o = 3k\Omega$

(2) $U_{omax} = \min\{ U_{CEQ} - U_{CES}，\ I_{CQ}R'_c \}$

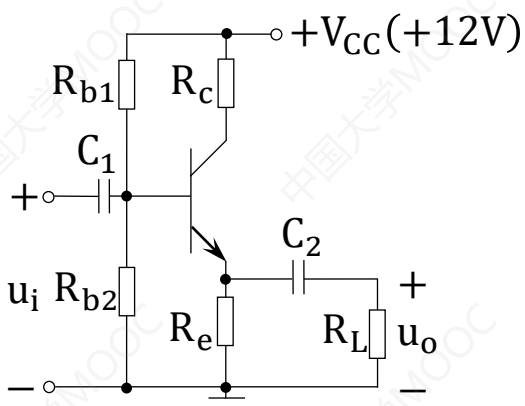
$= \min\{4.5815V - 0.7V，\ 1.85mA \cdot 1.5k\Omega\}$

$= \min\{3.8815V，\ 2.76V\}$

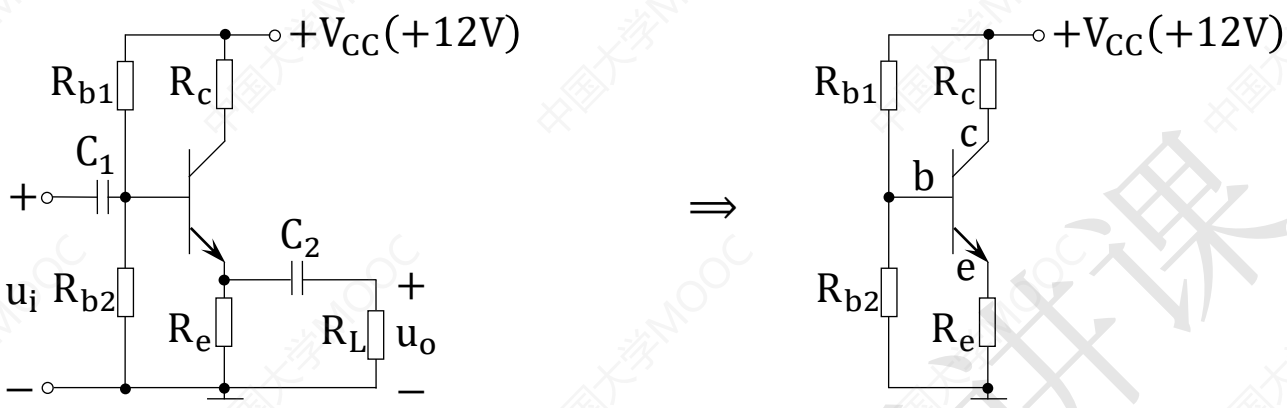
$= 2.76V$

共集电极放大电路的动态分析

例1. 已知三极管$\beta=30$，$R_{b1}=7.5k\Omega$，$R_{b2}=2.5k\Omega$，$R_c=2k\Omega$，$R_e=1k\Omega$
$R_L=2k\Omega$，静态时$U_{BEQ}=0.7V$，求$\dot{A}_u$、R_i、R_o、U_{omax}



一、静态分析



$R_{b1}=7.5k\Omega$

$R_{b2}=2.5k\Omega$

$R_c=2k\Omega$

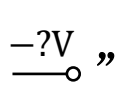
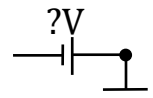
$R_e=1k\Omega$

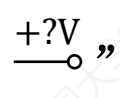
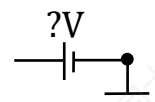
$$I_{BQ}=\frac{1}{(1+\beta)R_e}\cdot\left(\frac{R_{b2}}{R_{b1}+R_{b2}}V_{CC}-U_{BEQ}\right)$$
$$=\frac{1}{(1+30)\times 1k\Omega}\times\left(\frac{2.5k\Omega}{7.5k\Omega+2.5k\Omega}\times 12V-0.7V\right)$$
$$=0.074mA$$
$$I_{CQ}=\beta I_{BQ}=30\times 0.074mA=2.22mA$$
$$U_{CEQ}=V_{CC}-I_{CQ}\cdot R_c-(1+\beta)I_{BQ}\cdot R_e$$
$$=12V-2.22mA\times 2k\Omega-(1+30)\times 0.074mA\times 1k\Omega$$
$$=5.266V$$

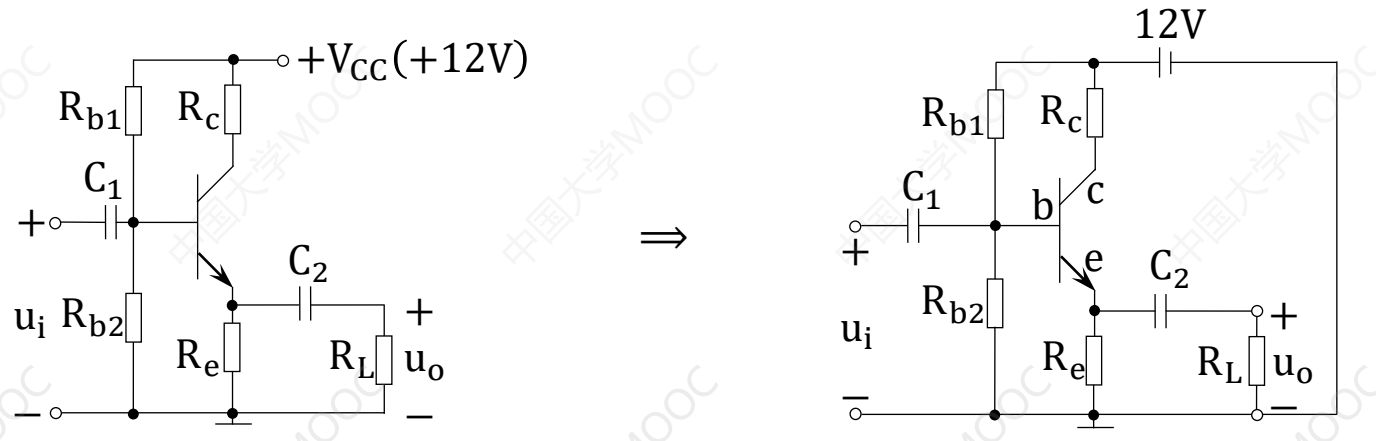
详见【基本放大电路】第1课【基本放大电路静态分析】

二、动态分析

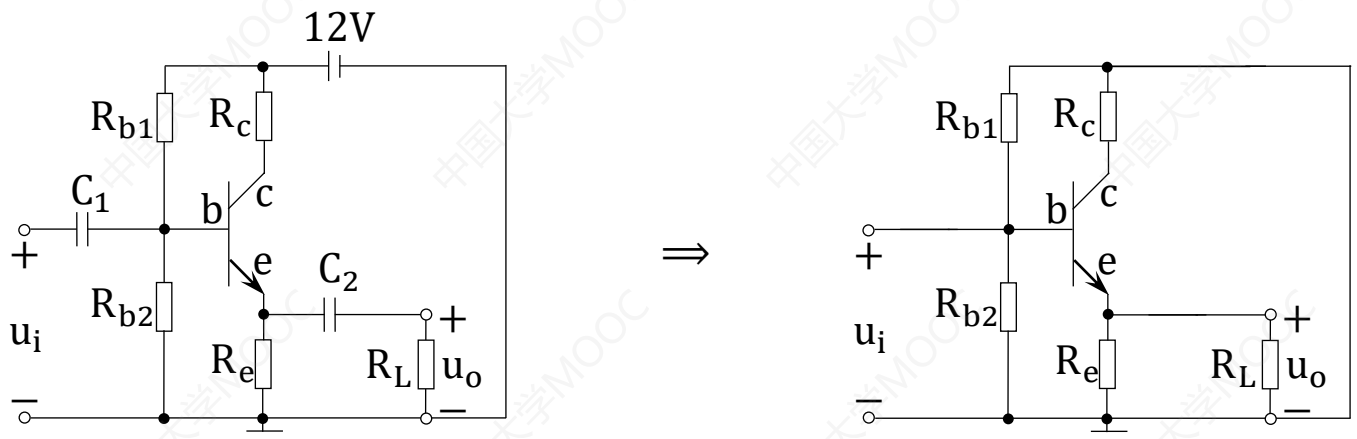
① 画微变等效电路

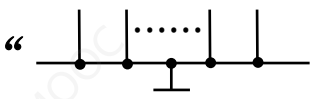
a、将“  ”变成“  ”

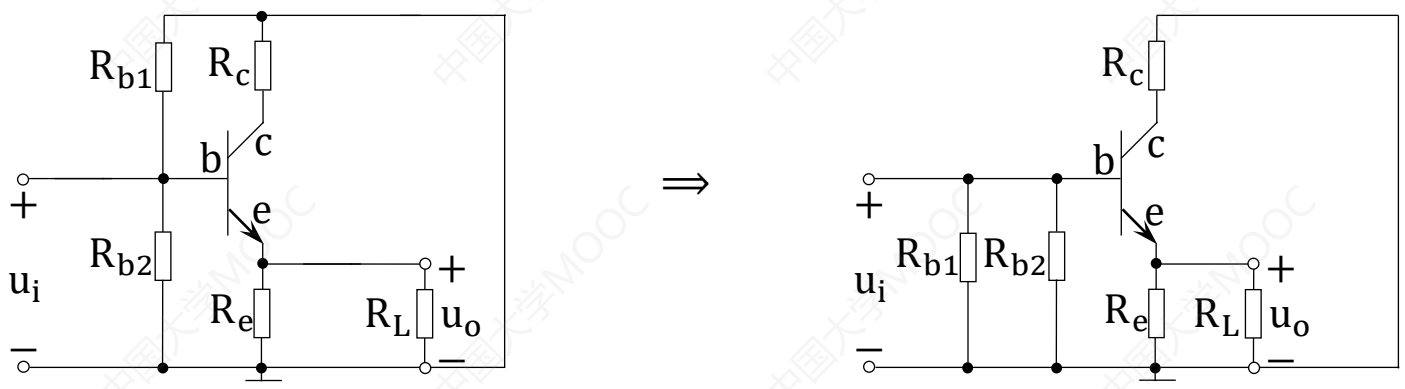
将“  ”变成“  ”

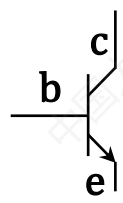


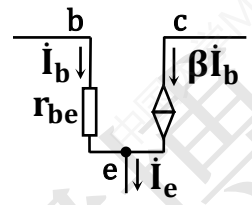
b、将电容与直流电源短路



c、让同“⊥”相连的线都变成“  ”

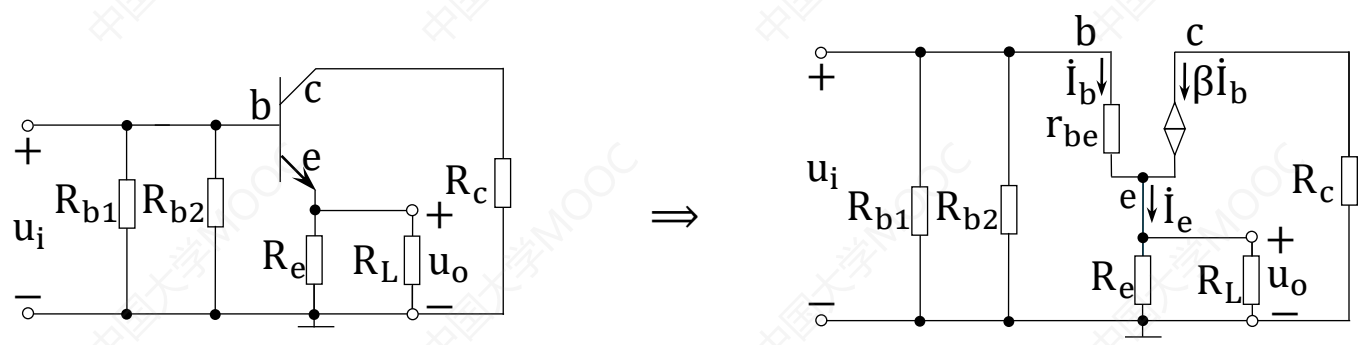


d、将 

变成 

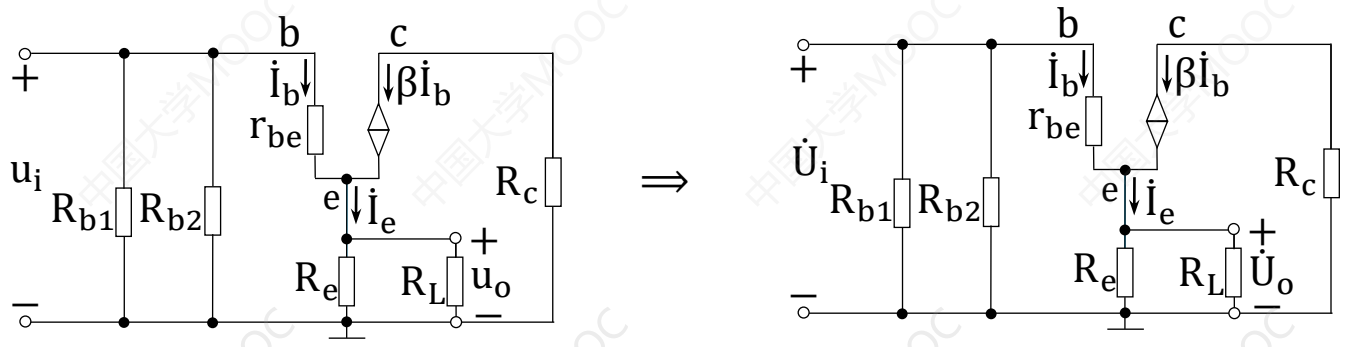
其中$r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{BQ}+I_{CQ}}$

【若题干没有给出r'_{bb}，则默认$r'_{bb} = 200\Omega$】



$$r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{BQ}+I_{CQ}} = 200\Omega + (1+30)\times\frac{26mV}{0.074mA+2.22mA} = 0.55k\Omega$$

e、将图中所有 $u_{啥}$ 变成 $\dot{U}_{啥}$



② 求几个等效电阻

a、将三极管 e 极与“⊥”之间的电阻等效成电阻 $\mathbf{R'_e}$

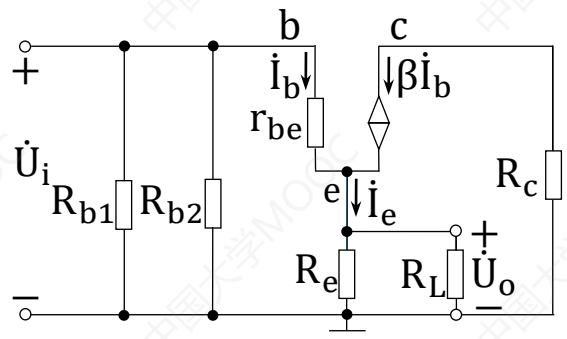
b、将三极管 b 极与 $\dot{\mathbf{U}}_\mathbf{i}$ 之间的电阻等效成电阻 $\mathbf{R'_b}$

c、若有“⏀”，则将“⏀”短路

若无“⏀”，则将 $\dot{\mathbf{U}}_\mathbf{i}$ 短路

将三极管外 b 极侧的电阻等效为电阻 $\mathbf{R''_b}$

d、将三极管 e 极与 $\mathbf{R_L}$ 之间的电阻等效成电阻 $\mathbf{R''_e}$



$I_{BQ}=0.074mA \quad I_{CQ}=2.22mA$

$U_{CEQ}=5.266V$

$r_{be}=0.55k\Omega$

$$R'_e=R_e//R_L=\frac{R_e\cdot R_L}{R_e+R_L}=\frac{1k\Omega\cdot 2k\Omega}{1k\Omega+2k\Omega}=0.67k\Omega$$

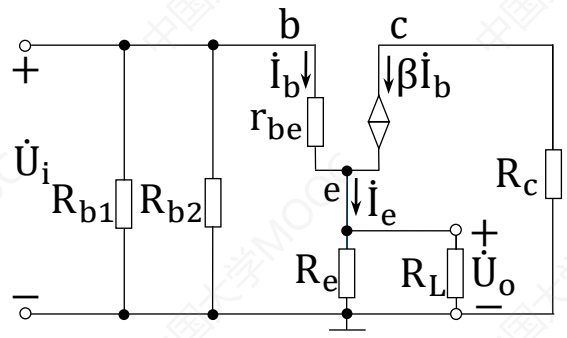
$$R'_b=R_{b1}//R_{b2}=\frac{R_{b1}\cdot R_{b2}}{R_{b1}+R_{b2}}=\frac{7.5k\Omega\cdot 2.5k\Omega}{7.5k\Omega+2.5k\Omega}=1.875k\Omega$$

$R''_b=0\Omega \qquad R''_e=R_e=1k\Omega$

③ $\dot{\mathbf{A}}_\mathbf{u}=\frac{(\mathbf{1+\beta})\mathbf{R'_e}}{\mathbf{r_{be}}+(\mathbf{1+\beta})\mathbf{R'_e}}$

$\mathbf{R_i=R'_b//[r_{be}+(1+\beta)R'_e]}$

$\mathbf{R_o=R''_e//\frac{R''_b+r_{be}}{1+\beta}}$



$I_{BQ}=0.074mA \quad I_{CQ}=2.22mA$

$U_{CEQ}=5.266V$

$r_{be}=0.55k\Omega$

$R'_e=0.67k\Omega \qquad R'_b=1.875k\Omega$

$R''_b=0\Omega \qquad R''_e=1k\Omega$

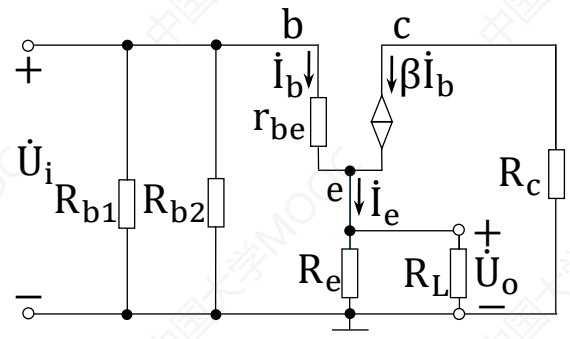
$$\dot{A}_u=\frac{(1+\beta)R'_e}{r_{be}+(1+\beta)R'_e}=\frac{(1+30)\times 0.67k\Omega}{0.55k\Omega+(1+30)\times 0.67k\Omega}=0.974$$

$$R_i=R'_b//[r_{be}+(1+\beta)R'_e]=\frac{R'_b\cdot[r_{be}+(1+\beta)R'_e]}{R'_b+[r_{be}+(1+\beta)R'_e]}=\frac{1.875k\Omega\cdot[0.55k\Omega+(1+30)\times 0.67k\Omega]}{1.875k\Omega+[0.55k\Omega+(1+30)0.67k\Omega]}=1.72k\Omega$$

$$R_o=R''_e//\frac{R''_b+r_{be}}{1+\beta}=\frac{R''_e\cdot\frac{R''_b+r_{be}}{1+\beta}}{R''_e+\frac{R''_b+r_{be}}{1+\beta}}=\frac{1k\Omega\cdot\frac{0\Omega+0.55k\Omega}{1+30}}{1k\Omega+\frac{0\Omega+0.55k\Omega}{1+30}}=0.017k\Omega$$

④ $\mathbf{U_{omax} = min\{ U_{CEQ} - U_{CES}，\ I_{CQ}R'_e \}}$

$\mathbf{U_{CES}}$ 题干会给，若没给则 $\mathbf{U_{CES} = U_{BEQ}}$



$I_{BQ} = 0.074mA$　$I_{CQ} = 2.22mA$

$U_{CEQ} = 5.266V$

$r_{be} = 0.55k\Omega$

$R'_e = 0.67k\Omega$　$R'_b = 1.875k\Omega$

$R''_b = 0\Omega$　$R''_e = 1k\Omega$

$\dot{A}_u = 0.974$

$R_i = 1.72k\Omega$

$R_o = 0.017k\Omega$

$$
\begin{aligned}
U_{omax} &= \min\{ U_{CEQ} - U_{CES}，\ I_{CQ}R'_e \} \\
&= \min\{5.266V - 0.7V，\ 2.22mA \cdot 0.67k\Omega\} \\
&= \min\{4.566V，\ 1.4874V\} \\
&= 1.4874V
\end{aligned}
$$

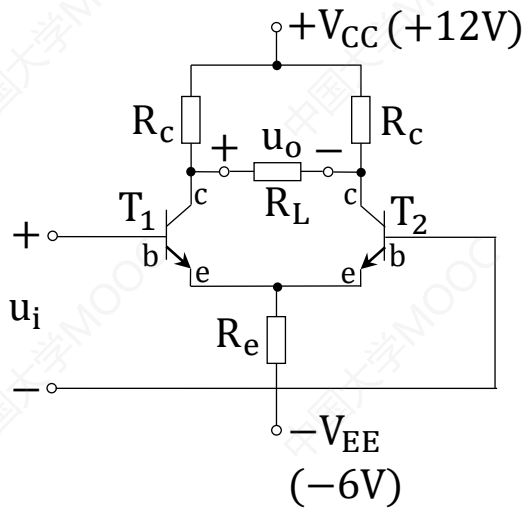
多级放大电路

例1. 如图所示差分电路，$\beta=80$，$R_c=10k\Omega$，$R_L=10k\Omega$

$R_e=5.3k\Omega$，$r'_{bb}=100\Omega$，$U_{BEQ}=0.7V$，则

(1) 求 T_1 和 T_2 的静态工作点

(2) 画出微变等效电路并计算 R_i、R_o、A_d、A_c

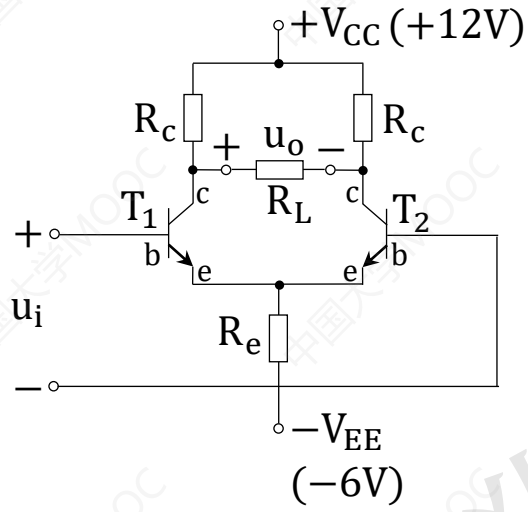


一、 静态分析

① 求两个三极管的 I_{EQ}

a、若图中有恒流源“ ⊖↓I ”， $I_{EQ1}=I_{EQ2}=0.5I$

b、若图中无恒流源“ ⊖↓I ”， $I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}$

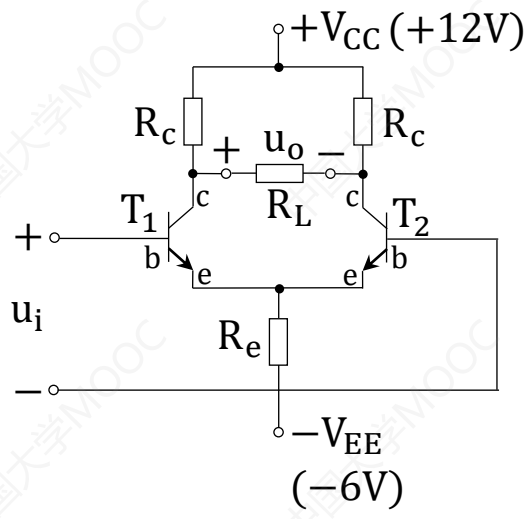


(1) $I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}$

$=\frac{6V-0.7V}{2\times5.3k\Omega}$

$=0.5mA$

② $I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}$、$I_{CQ1}=I_{CQ2}\approx I_{EQ1}$



(1) $I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}$

$=\frac{6V-0.7V}{2\times5.3k\Omega}$

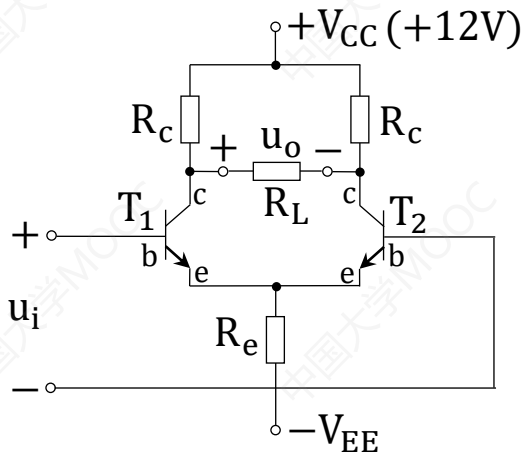
$=0.5mA$

$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$

$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$

③ 若有 $\mathbf{u_o}$ 的支路横跨两个三极管，则为双端输出

若有 $\mathbf{u_o}$ 的支路只连接一个三极管，则为单端输出



双端输出 (−6V)

$$(1)\ I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}=\frac{6V-0.7V}{2\times5.3k\Omega}=0.5mA$$

$$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$$

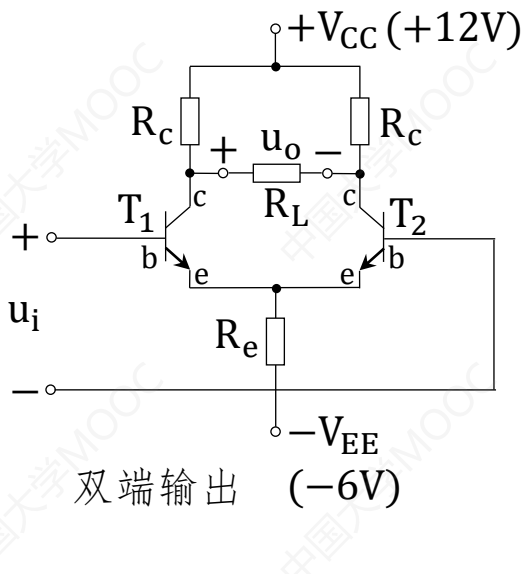
$$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$$

④ 求两个三极管的 $\mathbf{c}$ 极电位 $\mathbf{V_{cn}}$

a、双端输出： $\mathbf{V_{c1}=V_{c2}=V_{CC}-I_{CQ1}\cdot R_c}$

b、单端输出： 输出端 $\mathbf{V_{cn}}$ 满足 $\mathbf{\frac{V_{CC}-V_{cn}}{R_{cn}}=I_{CQn}+\frac{V_{cn}}{R_L}}$

另一端 $\mathbf{V_{cm}=V_{CC}-I_{CQm}\cdot}$ 该$\mathbf{c}$极与$\mathbf{V_{CC}}$之间的电阻



双端输出 (−6V)

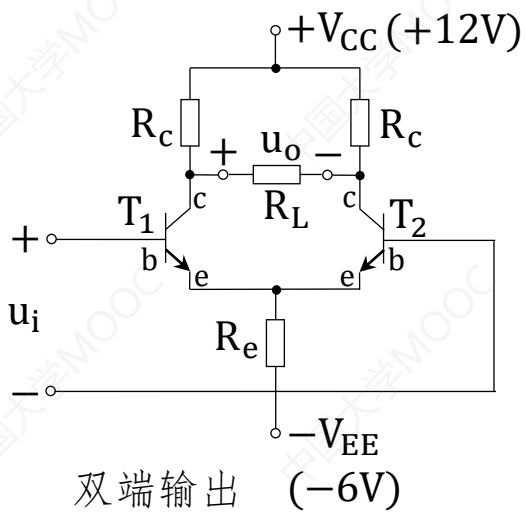
$$(1)\ I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}=\frac{6V-0.7V}{2\times5.3k\Omega}=0.5mA$$

$$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$$

$$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$$

$$V_{c1}=V_{c2}=V_{CC}-I_{CQ1}\cdot R_c=12V-0.5mA\cdot10k\Omega=7V$$

⑤ 求两个三极管的 $\mathbf{U_{CEQn}=V_{cn}+U_{BEQ}}$



双端输出 (−6V)

$$(1)\ I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}=\frac{6V-0.7V}{2\times5.3k\Omega}=0.5mA$$

$$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$$

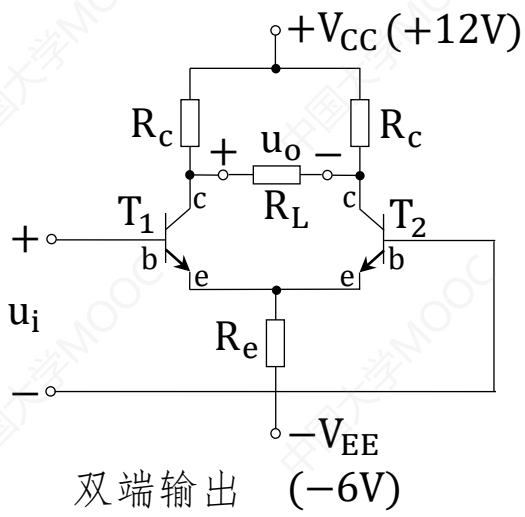
$$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$$

$$V_{c1}=V_{c2}=V_{CC}-I_{CQ1}\cdot R_c=12V-0.5mA\cdot10k\Omega=7V$$

$$U_{CEQ1}=V_{c1}+U_{BEQ}=7V+0.7V=7.7V$$

$$U_{CEQ2}=V_{c2}+U_{BEQ}=7V+0.7V=7.7V$$

二、动态分析



(1) $I_{EQ1} = I_{EQ2} = 0.5mA$

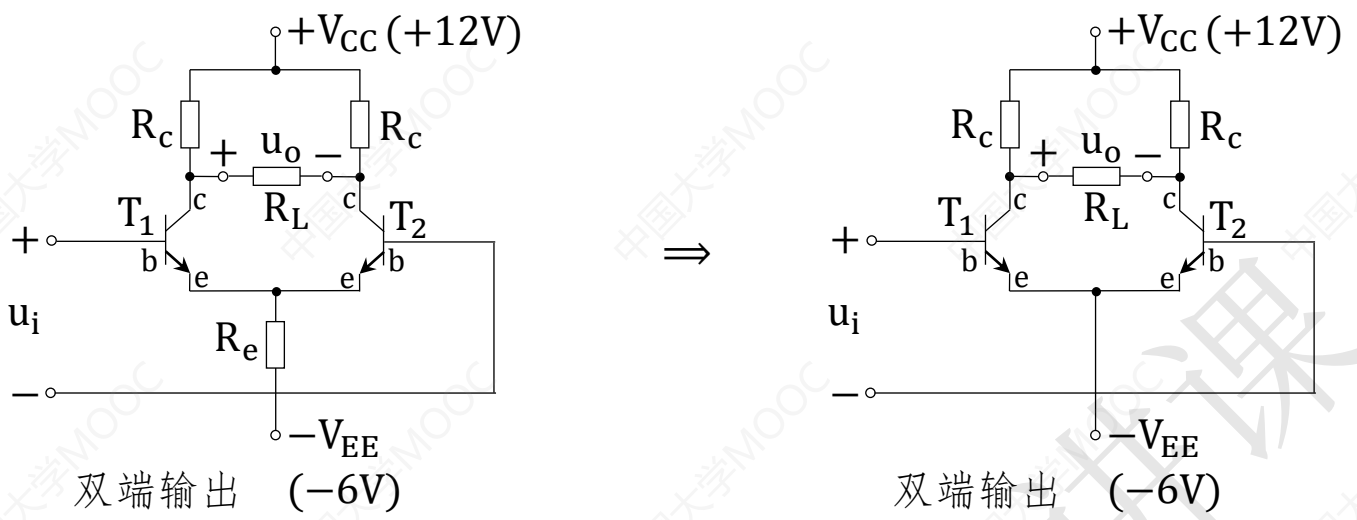
$I_{BQ1} = I_{BQ2} = 6.17\mu A$

$I_{CQ1} = I_{CQ2} \approx 0.5mA$

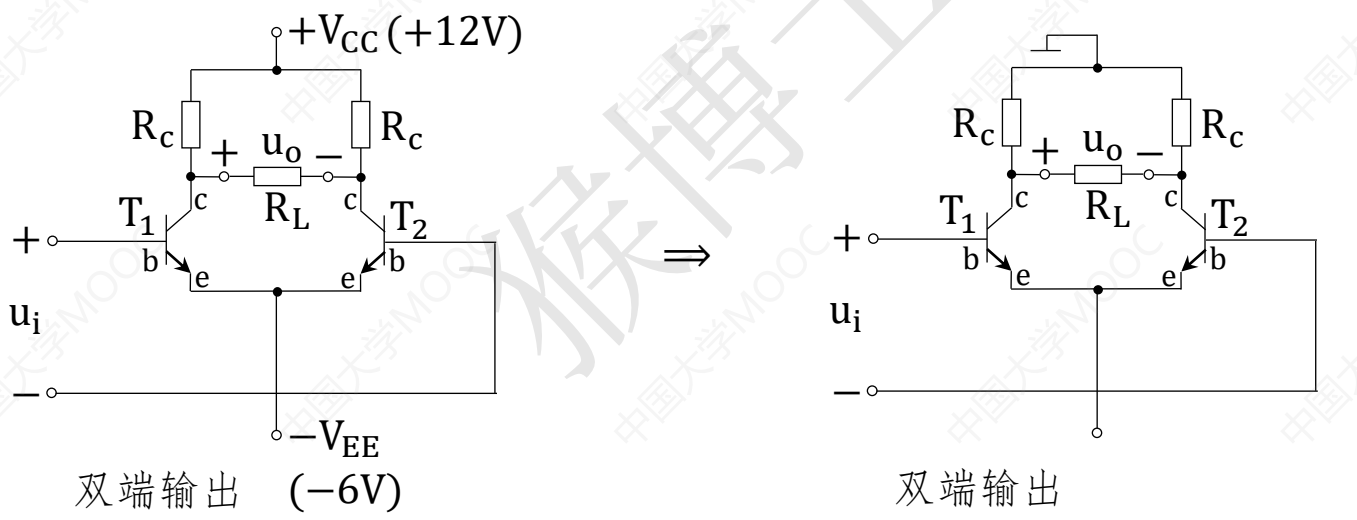
$U_{CEQ1} = U_{CEQ2} = 7.7V$

① 画微变等效电路

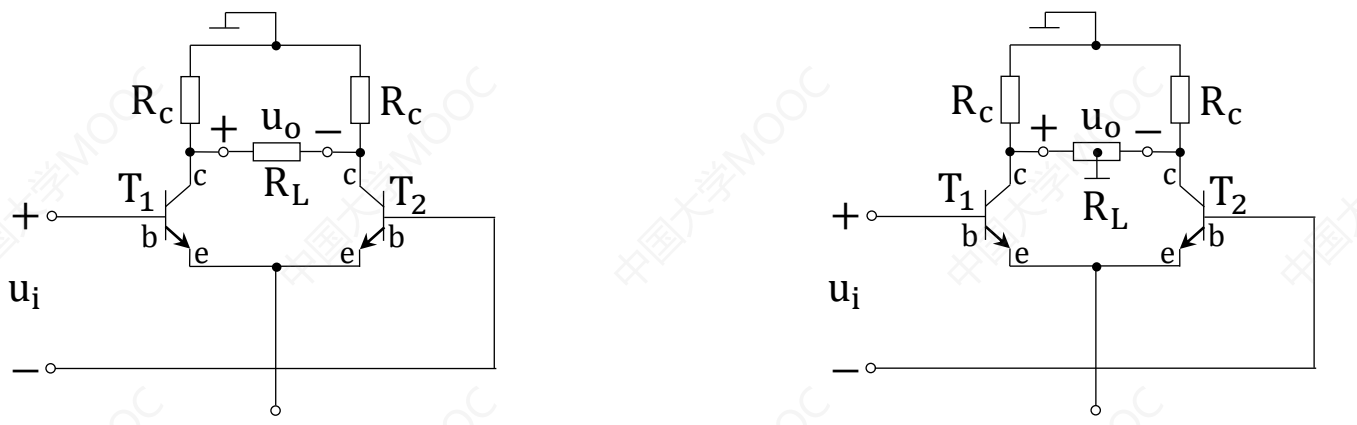
a、将 $-V_{EE}$ 的竖线上所有的元件短路

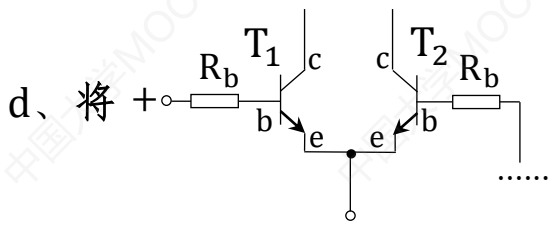


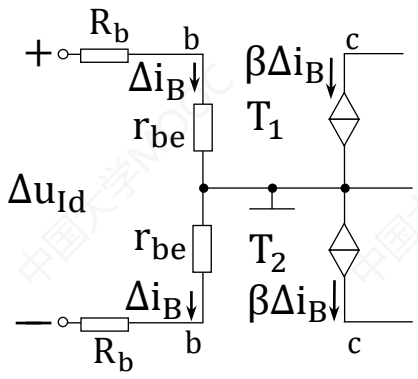
b、将 $+V_{CC}$ 接“⊥”，并去掉 $+V_{CC}$ 与 $-V_{EE}$



c、若为双端输出，则有 u_o 的支路中点处接“⊥”

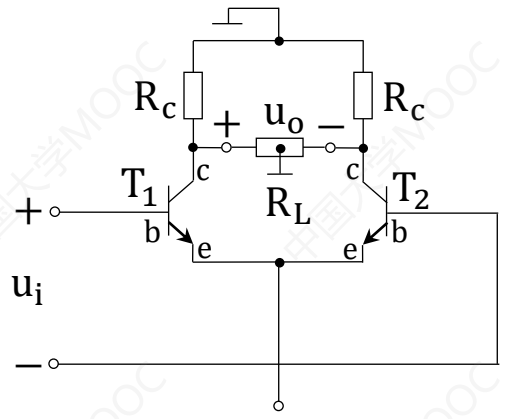


d、将 

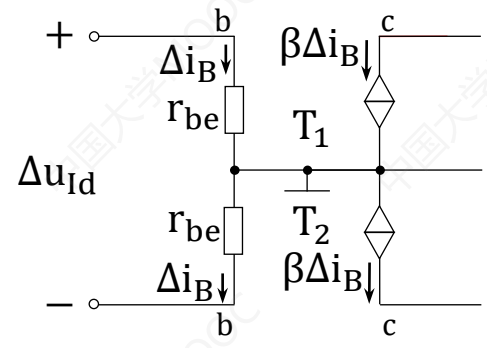
变成 

其中$\mathbf{r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{EQ1}}}$

【若题干没给$\mathbf{r'_{bb}}$，则默认$\mathbf{r'_{bb} = 200\Omega}$】

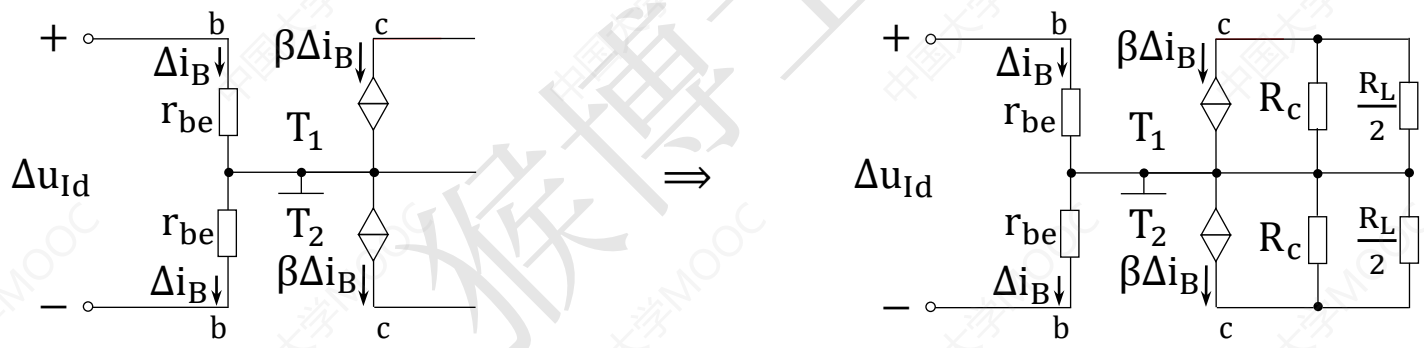


双端输出

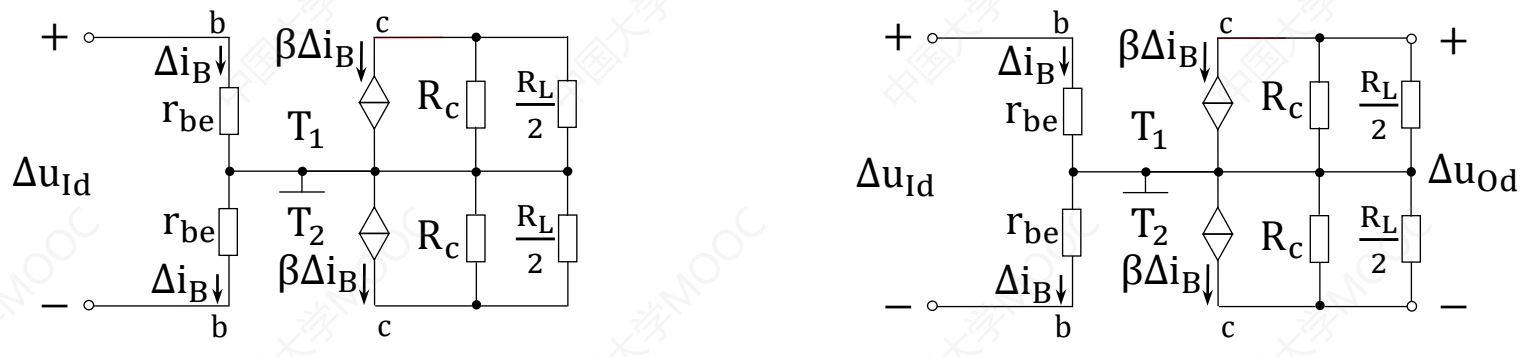


$$r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{EQ1}}$$
$$= 100\Omega + (1+80)\frac{26mV}{0.5mA}$$
$$= 4312\Omega$$

e、将各三极管c端同“⊥”间的电阻接到等效电路中



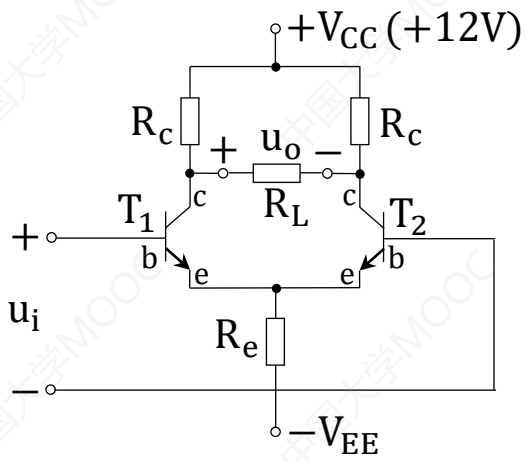
f、在完整的$\mathbf{R_L}$上下端画上 $\circ +$ $\Delta\mathbf{u_{Od}}$ $\circ -$



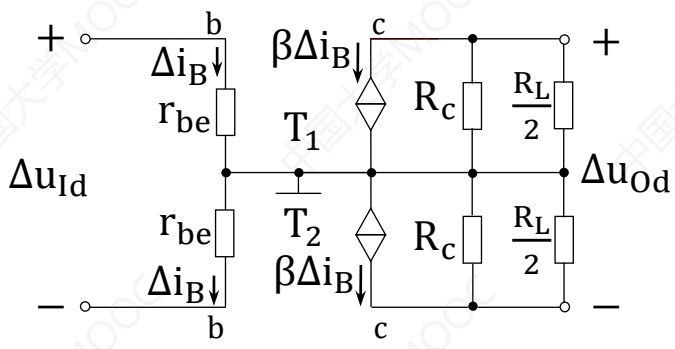
②

	R_i	R_o	A_d	A_c
双端输出	$2(R_b+r_{be})$	$2R_c$	$\frac{-\beta(R_c//\frac{R_L}{2})}{R_b+r_{be}}$	0
单端输出	$2(R_b+r_{be})$	R_c	$\frac{-\beta(R_c//R_L)}{2(R_b+r_{be})}$	0 (恒流源)

【R_b为三极管外 b 极上的电阻】



双端输出 $(-6V)$



(1) $I_{EQ1}=I_{EQ2}=0.5mA$

$I_{BQ1}=I_{BQ2}=6.17\mu A$

$I_{CQ1}=I_{CQ2}\approx 0.5mA$

$U_{CEQ1}=U_{CEQ2}=7.7V$

(2) $r_{be}=4312\Omega$

$R_i=2(R_b+r_{be})=2\times(0+4312\Omega)=8624\Omega$

$R_o=2R_c=2\times 10k\Omega=20k\Omega$

$$A_d=\frac{-\beta(R_c//\frac{R_L}{2})}{r_{be}}=\frac{-\beta\frac{R_c\cdot\frac{R_L}{2}}{R_c+\frac{R_L}{2}}}{r_{be}}=\frac{-80\times\frac{10k\Omega\cdot\frac{10k\Omega}{2}}{10k\Omega+\frac{10k\Omega}{2}}}{4312\Omega}=-61.84$$

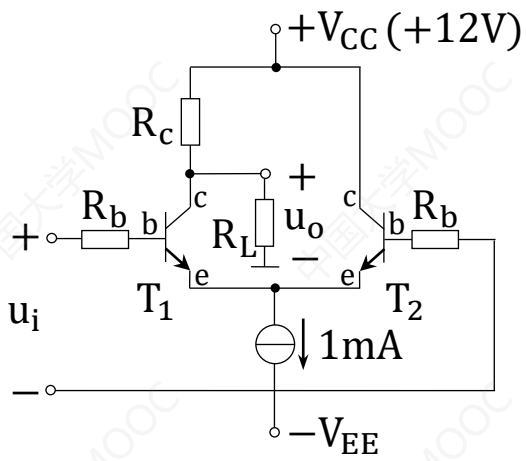
$A_c=0$

例2. 如图所示差分电路，$\beta=80$，$R_c=10k\Omega$，$R_L=10k\Omega$

$R_b=5k\Omega$，$r'_{bb}=100\Omega$，$U_{BEQ}=0.7V$，则

(1) 求 T_1 和 T_2 的静态工作点

(2) 画出微变等效电路并计算 R_i、R_o、A_d、A_c

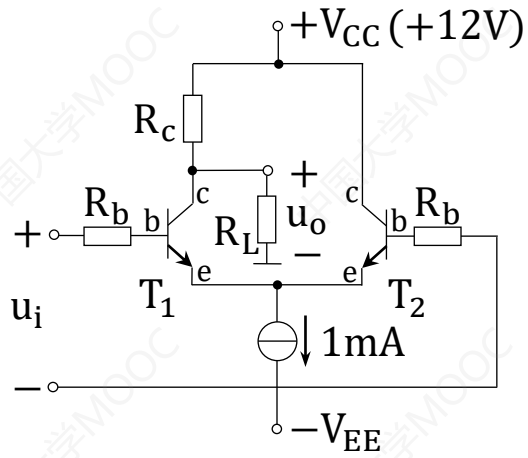


一、静态分析

① 求两个三极管的 $\mathbf{I_{EQ}}$

a、若图中有恒流源“⊖↓I”，$\mathbf{I_{EQ1}=I_{EQ2}=0.5I}$

b、若图中无恒流源“⊖↓I”，$\mathbf{I_{EQ1}=I_{EQ2}=\frac{V_{EE}-U_{BEQ}}{2R_e}}$

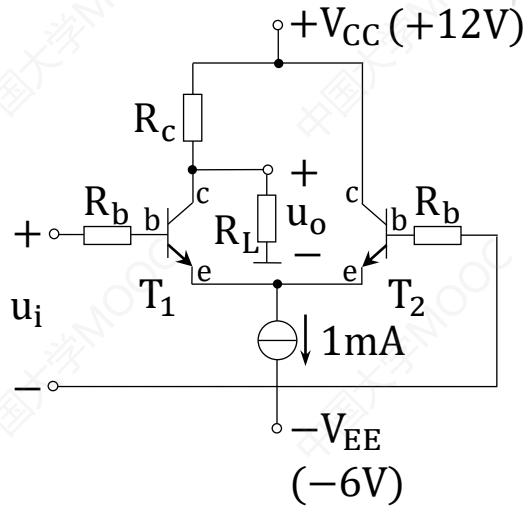


(1) $I_{EQ1}=I_{EQ2}=0.5I$

$=0.5\times1mA$

$=0.5mA$

② $\mathbf{I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}}$、$\mathbf{I_{CQ1}=I_{CQ2}\approx I_{EQ1}}$



(1) $I_{EQ1}=I_{EQ2}=0.5I$

$=0.5\times1mA$

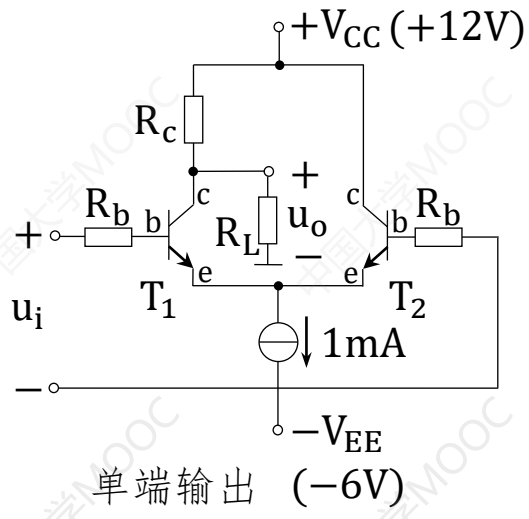
$=0.5mA$

$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$

$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$

③ 若有 $\mathbf{u_o}$ 的支路横跨两个三极管，则为双端输出

若有 $\mathbf{u_o}$ 的支路只连接一个三极管，则为单端输出



(1) $I_{EQ1}=I_{EQ2}=0.5I$

$=0.5\times1mA$

$=0.5mA$

$I_{BQ1}=I_{BQ2}=\frac{I_{EQ1}}{1+\beta}=\frac{0.5mA}{1+80}=6.17\mu A$

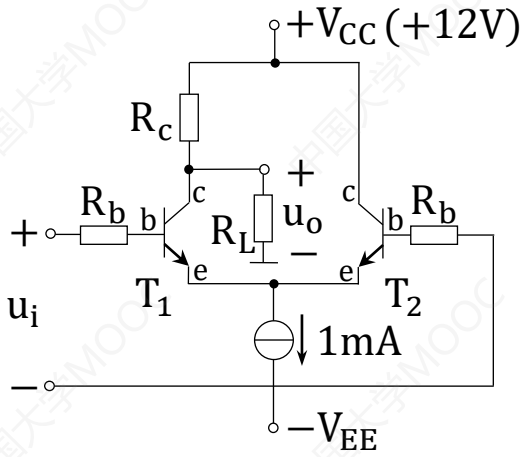
$I_{CQ1}=I_{CQ2}\approx I_{EQ1}=0.5mA$

④ 求两个三极管的 c 极电位 $\mathbf{V_{cn}}$

a、双端输出：$\mathbf{V_{c1} = V_{c2} = V_{CC} - I_{CQ1} \cdot R_c}$

b、单端输出：输出端 $\mathbf{V_{cn}}$ 满足 $\frac{V_{CC}-V_{cn}}{R_{cn}} = I_{CQn} + \frac{V_{cn}}{R_L}$

另一端 $\mathbf{V_{cm}} = V_{CC} - I_{CQm} \cdot$ 该c极与$\mathbf{V_{CC}}$之间的电阻



单端输出 $(-6V)$

(1) $I_{EQ1} = I_{EQ2} = 0.5I$

$= 0.5 \times 1mA$

$= 0.5mA$

$I_{BQ1} = I_{BQ2} = \frac{I_{EQ1}}{1+\beta} = \frac{0.5mA}{1+80} = 6.17\mu A$

$I_{CQ1} = I_{CQ2} \approx I_{EQ1} = 0.5mA$

$\frac{V_{CC}-V_{c1}}{R_{c1}} = I_{CQ1} + \frac{V_{c1}}{R_L}$

$\Longrightarrow \frac{12V-V_{c1}}{10k\Omega} = I_{CQ1} + \frac{V_{c1}}{10k\Omega}$

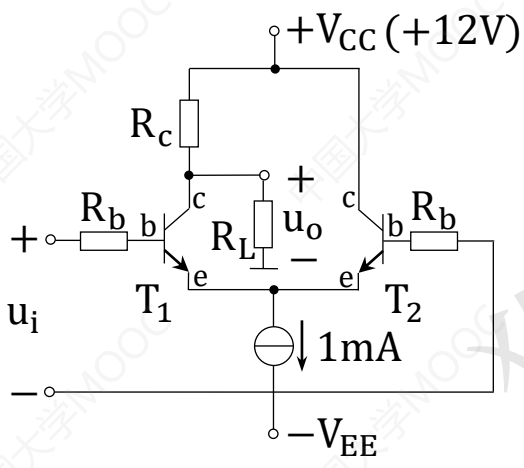
$\Longrightarrow 12V - V_{c1} = 0.5mA \times 10k\Omega + V_{c1}$

$\Longrightarrow 2V_{c1} = 7V$

$\Longrightarrow V_{c1} = 3.5V$

$V_{c2} = V_{CC} - I_{CQ2} \cdot 0\Omega = 12V - 0.5mA \cdot 0 = 12V$

⑤ 求两个三极管的 $\mathbf{U_{CEQn} = V_{cn} + U_{BEQ}}$



单端输出 $(-6V)$

(1) $I_{EQ1} = I_{EQ2} = 0.5I$

$= 0.5 \times 1mA$

$= 0.5mA$

$I_{BQ1} = I_{BQ2} = \frac{I_{EQ1}}{1+\beta} = \frac{0.5mA}{1+80} = 6.17\mu A$

$I_{CQ1} = I_{CQ2} \approx I_{EQ1} = 0.5mA$

$\frac{V_{CC}-V_{c1}}{R_{c1}} = I_{CQ1} + \frac{V_{c1}}{R_L}$

$\Longrightarrow \frac{12V-V_{c1}}{10k\Omega} = I_{CQ1} + \frac{V_{c1}}{10k\Omega}$

$\Longrightarrow 12V - V_{c1} = 0.5mA \times 10k\Omega + V_{c1}$

$\Longrightarrow 2V_{c1} = 7V$

$\Longrightarrow V_{c1} = 3.5V$

$V_{c2} = V_{CC} - I_{CQ2} \cdot 0\Omega = 12V - 0.5mA \cdot 0 = 12V$

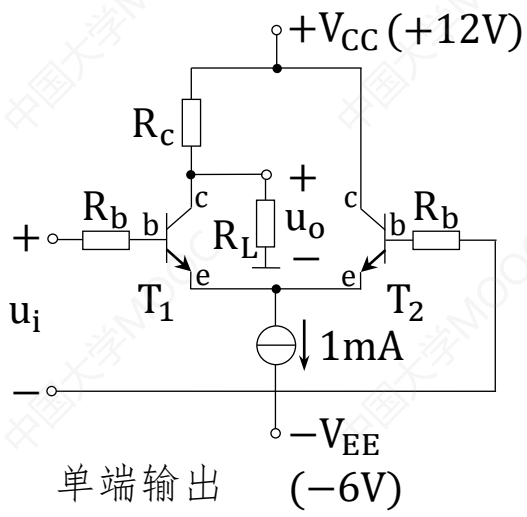
$U_{CEQ1} = V_{c1} + U_{BEQ}$

$= 3.5V + 0.7V$

$= 4.2V$

$U_{CEQ2} = V_{c2} + U_{BEQ} = 12V + 0.7V = 12.7V$

二、动态分析



(1) $I_{EQ1} = I_{EQ2} = 0.5mA$

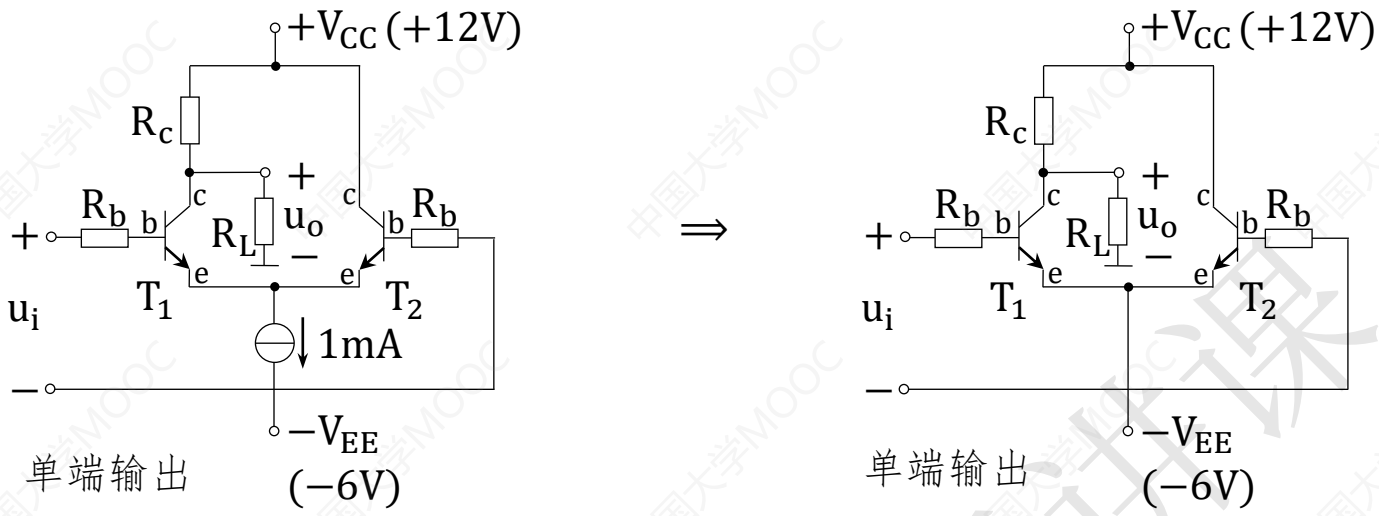
$I_{BQ1} = I_{BQ2} = 6.17\mu A$

$I_{CQ1} = I_{CQ2} \approx 0.5mA$

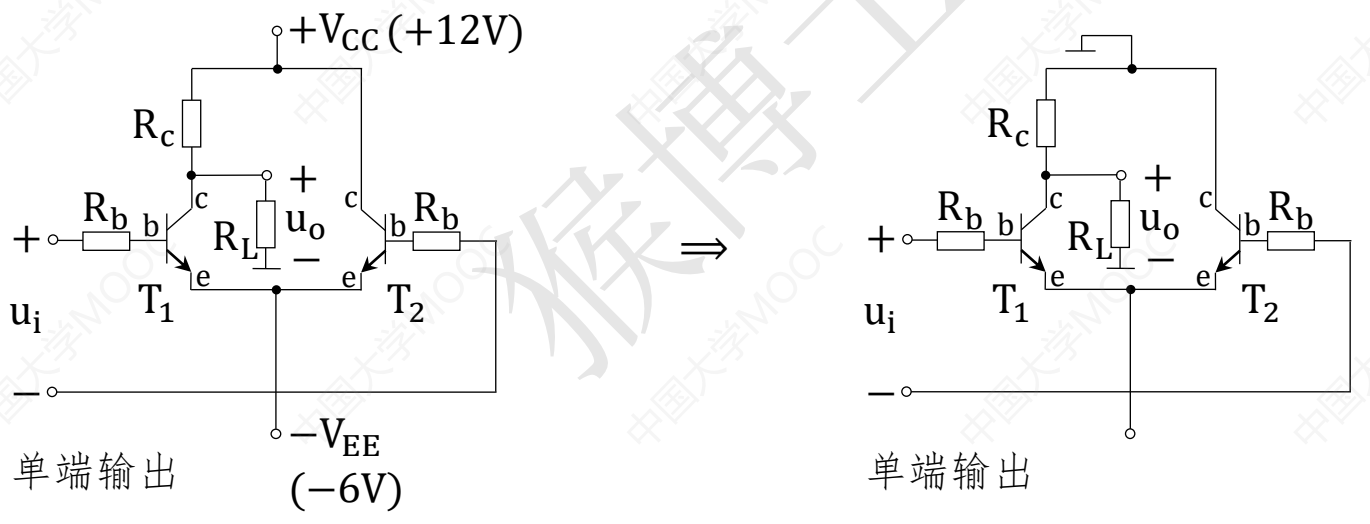
$U_{CEQ1} = 4.2V$， $U_{CEQ2} = 12.7V$

① 画微变等效电路

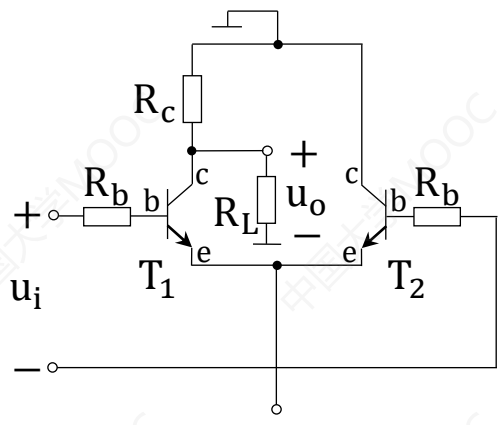
a、将 $-V_{EE}$ 的竖线上所有的元件短路

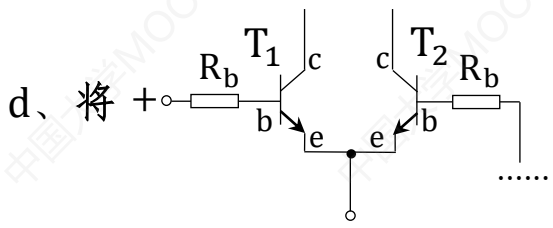


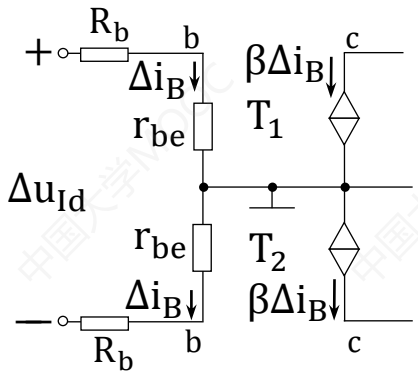
b、将 $+V_{CC}$ 接“⊥”，并去掉 $+V_{CC}$ 与 $-V_{EE}$



c、若为双端输出，则有 u_o 的支路中点处接“⊥”

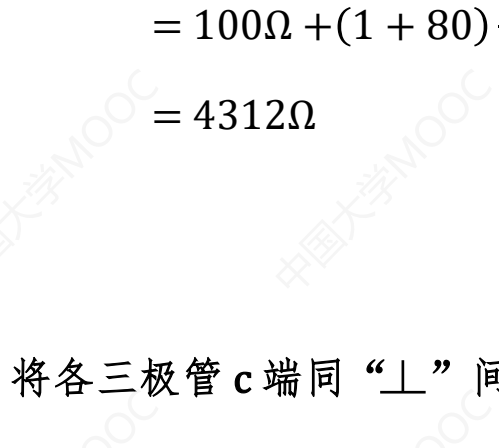


d、将 

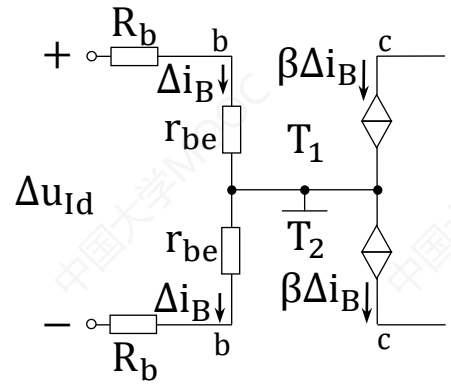
变成 

其中$\mathbf{r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{EQ1}}}$

【若题干没给$\mathbf{r'_{bb}}$，则默认$\mathbf{r'_{bb} = 200\Omega}$】



单端输出

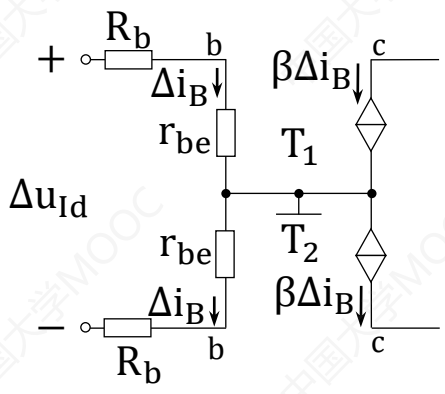
$\Rightarrow$ 

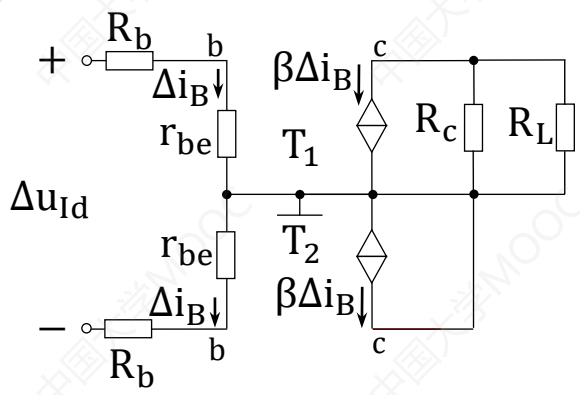
(2) $r_{be} = r'_{bb} + (1+\beta)\frac{26mV}{I_{EQ1}}$

$= 100\Omega + (1+80)\frac{26mV}{0.5mA}$

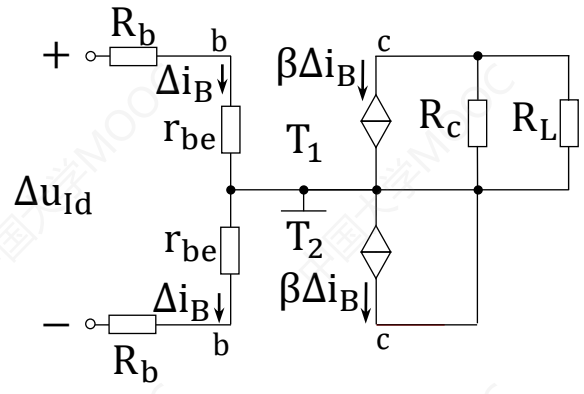
$= 4312\Omega$

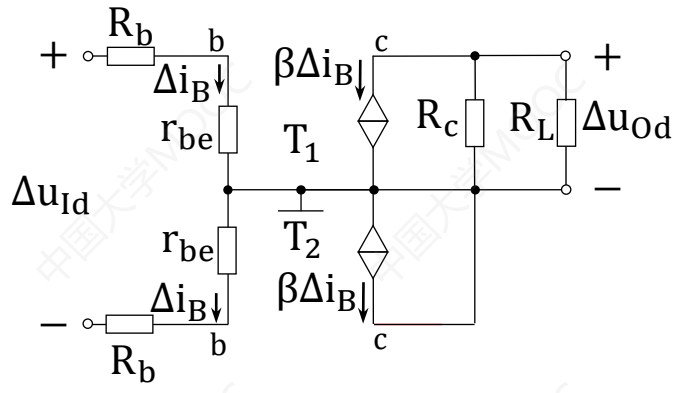
e、将各三极管c端同“⊥”间的电阻接到等效电路中



$\Rightarrow$ 

f、在完整的$\mathbf{R_L}$上下端画上 $\circ +$ $\Delta \mathbf{u_{Od}}$ $\circ -$

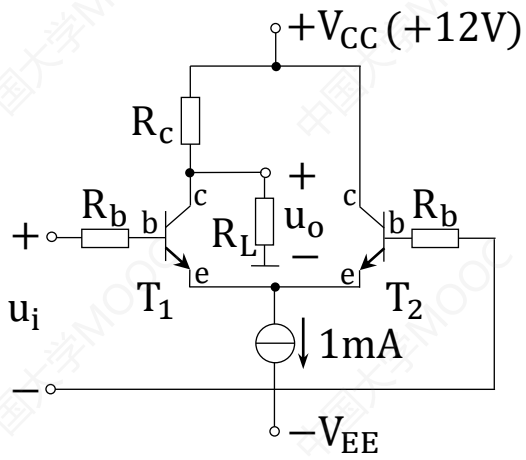


$\Rightarrow$ 

②

	R_i	R_o	A_d	A_c
双端输出	$2(R_b+r_{be})$	$2R_c$	$\frac{-\beta(R_c//\frac{R_L}{2})}{R_b+r_{be}}$	0
单端输出	$2(R_b+r_{be})$	R_c	$\frac{-\beta(R_c//R_L)}{2(R_b+r_{be})}$	0 (恒流源)

【R_b为三极管外 b 极上的电阻】



(1) $I_{EQ1}=I_{EQ2}=0.5mA$

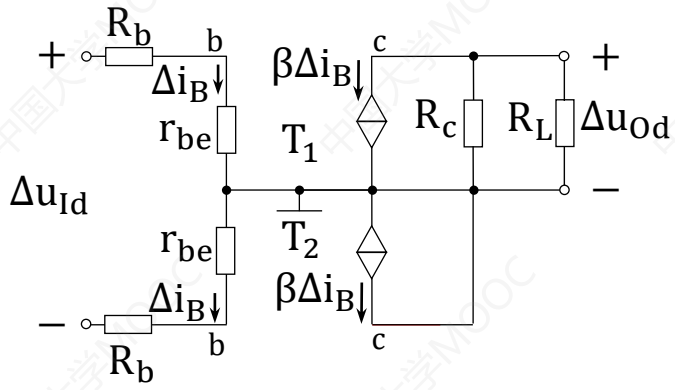
$I_{BQ1}=I_{BQ2}=6.17\mu A$

$I_{CQ1}=I_{CQ2}\approx 0.5mA$

$U_{CEQ1}=4.2V,\ U_{CEQ2}=12.7V$

(2) $r_{be}=4312\Omega$

单端输出 $(-6V)$



$R_i=2(R_b+r_{be})=2\times(5k\Omega+4312\Omega)=18624\Omega$

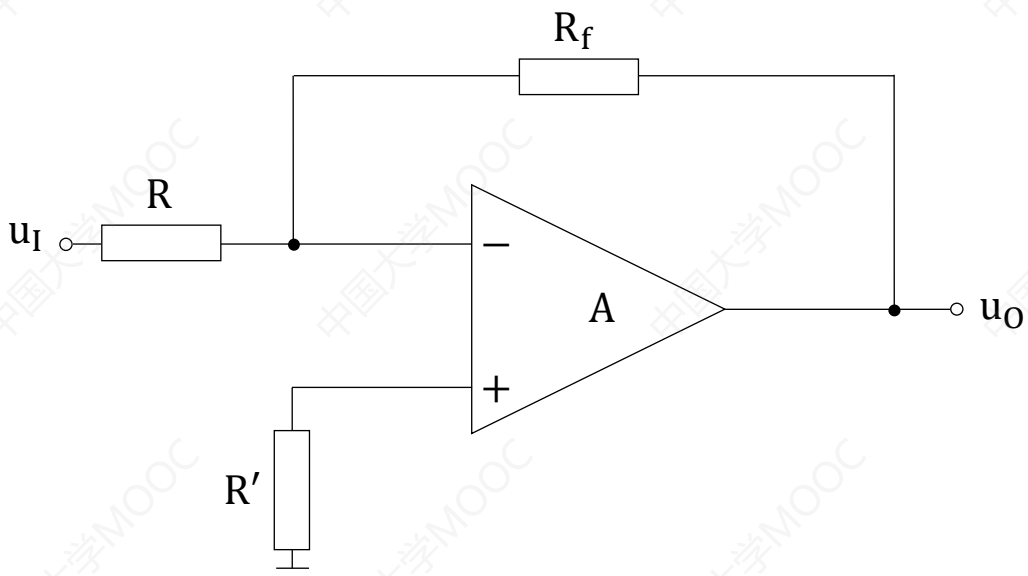
$R_o=R_c=10k\Omega$

$$A_d=\frac{-\beta(R_c//R_L)}{2(R_b+r_{be})}=\frac{-\beta\frac{R_c\cdot R_L}{R_c+R_L}}{2(R_b+r_{be})}=\frac{-80\frac{10k\Omega\cdot 10k\Omega}{10k\Omega+10k\Omega}}{2(5k\Omega+4312\Omega)}=-21.48$$

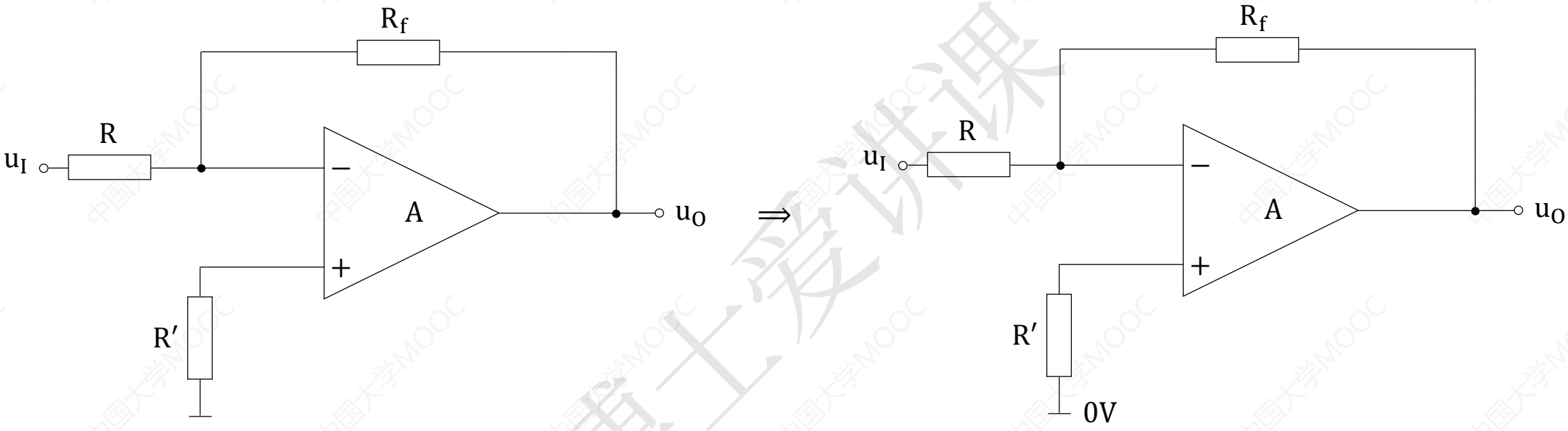
$A_c=0$

反相比例运算电路

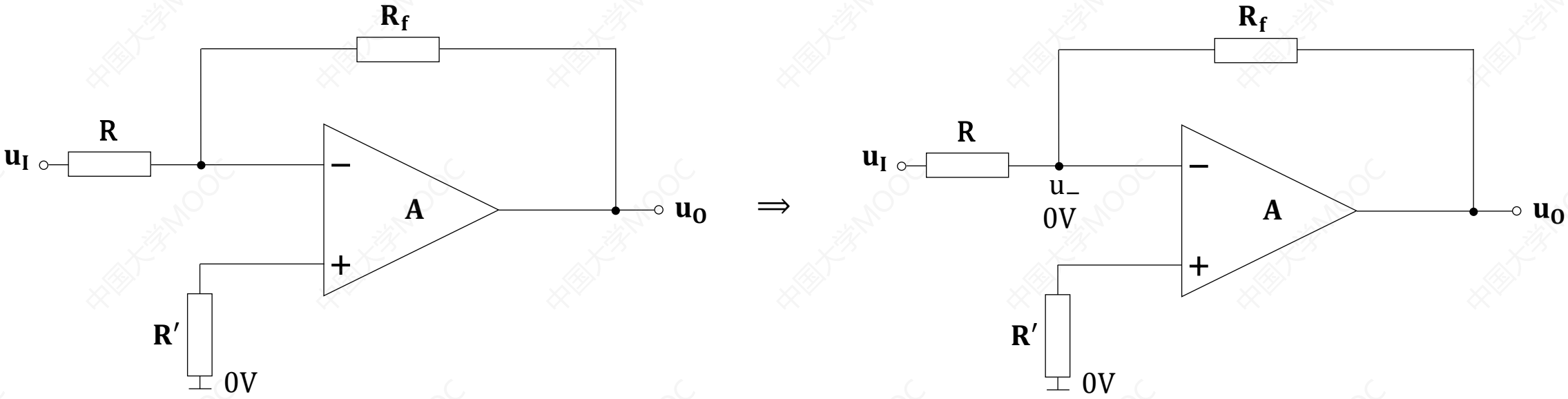
例1. 电路如图所示，已知u_I、R、R_f、R′，求u_O



① 将各电压直接看做该点的电位，接地处电位为**0V**



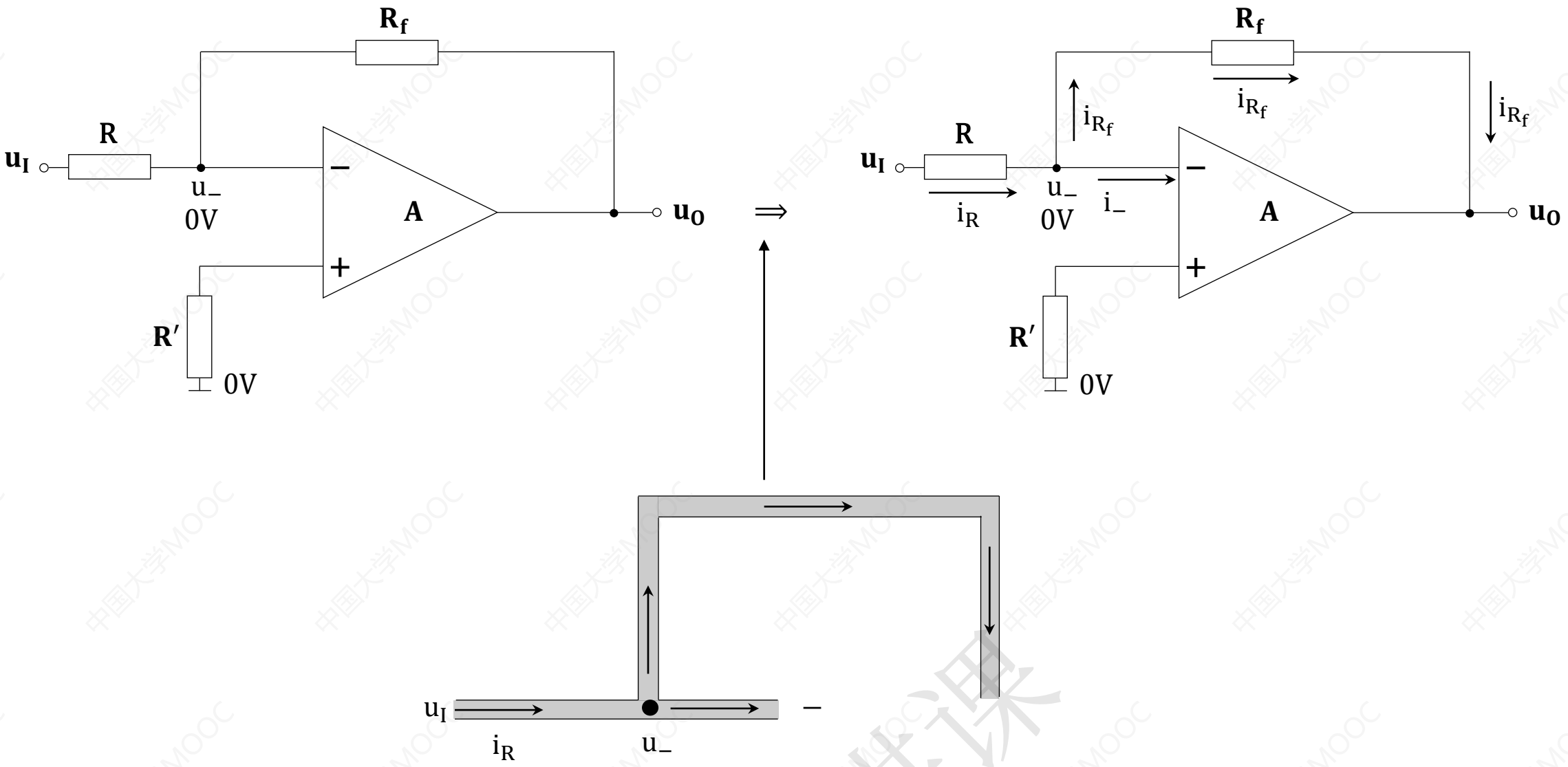
② 在“**−**”号前面标上**u_-**，**u_-** 处的电位 = **0V**



③ 画出“−”输入端以及支路的电流方向

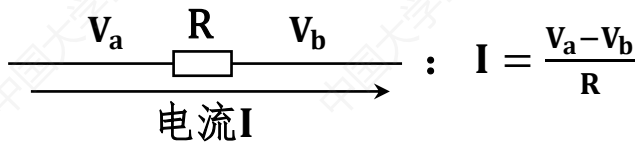
a、假设电流从输入电压处流入

b、将电流看做水流，将导线与电阻看做水管，画出水流方向即电流方向

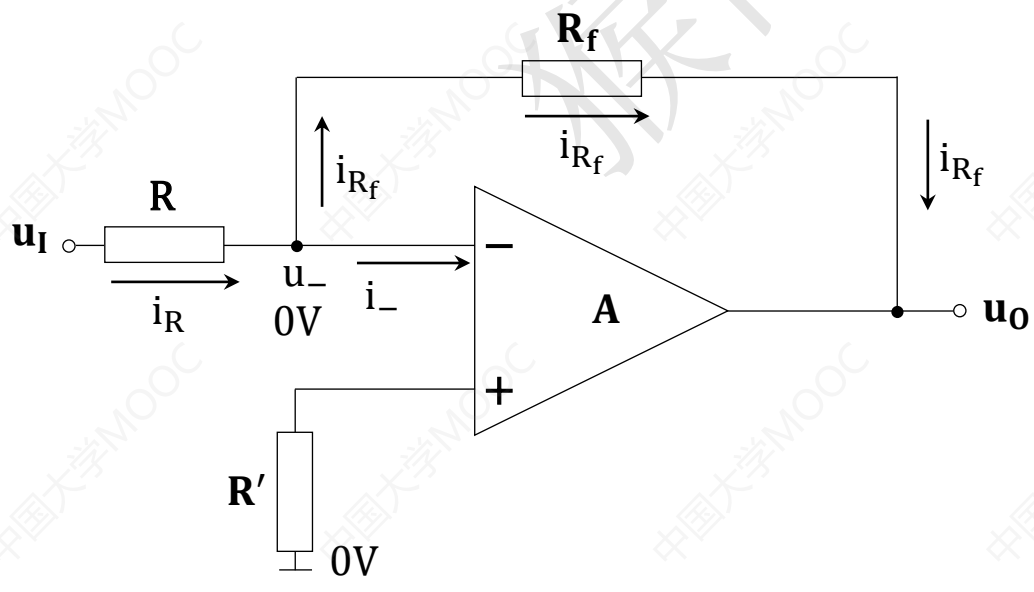


④ 分析 u_- 处、支路中分支节点处的电流大小关系

“−”号与 u_- 之间的电流为0



：$I = \frac{V_a - V_b}{R}$



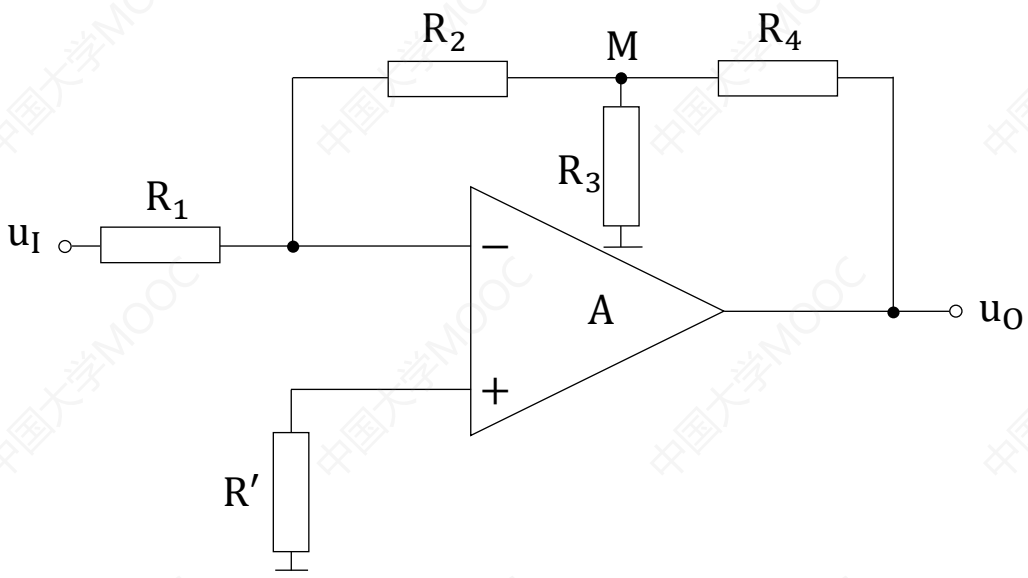
$$i_R = i_{R_f} \Longrightarrow \frac{u_I - u_-}{R} = \frac{u_- - u_O}{R_f} \Longrightarrow \frac{u_I - 0V}{R} = \frac{0V - u_O}{R_f}$$

$$\Longrightarrow \frac{u_I}{R} = -\frac{u_O}{R_f}$$

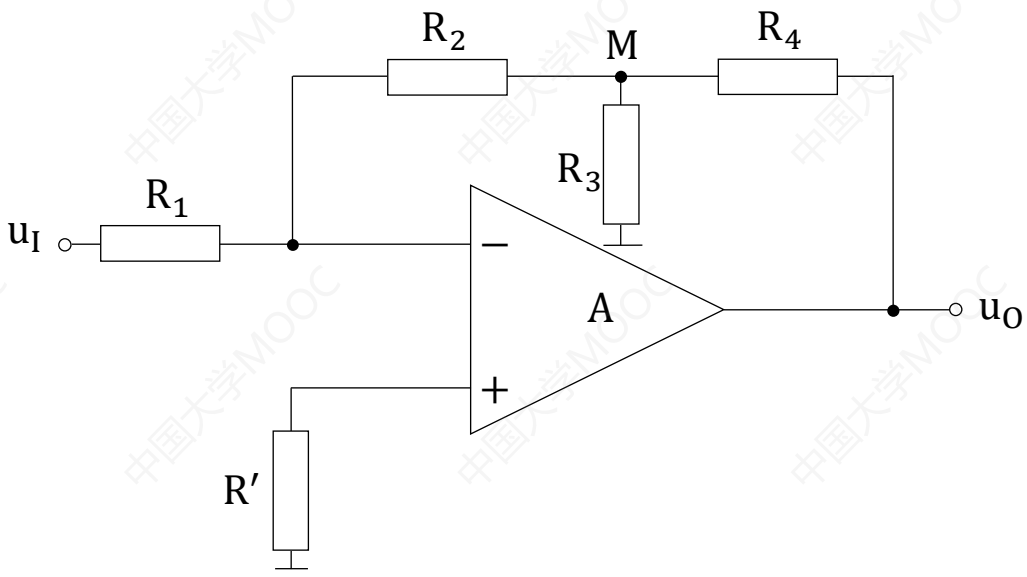
$$\Longrightarrow \frac{u_O}{R_f} = -\frac{u_I}{R}$$

$$\Longrightarrow u_O = -\frac{R_f}{R} \cdot u_I$$

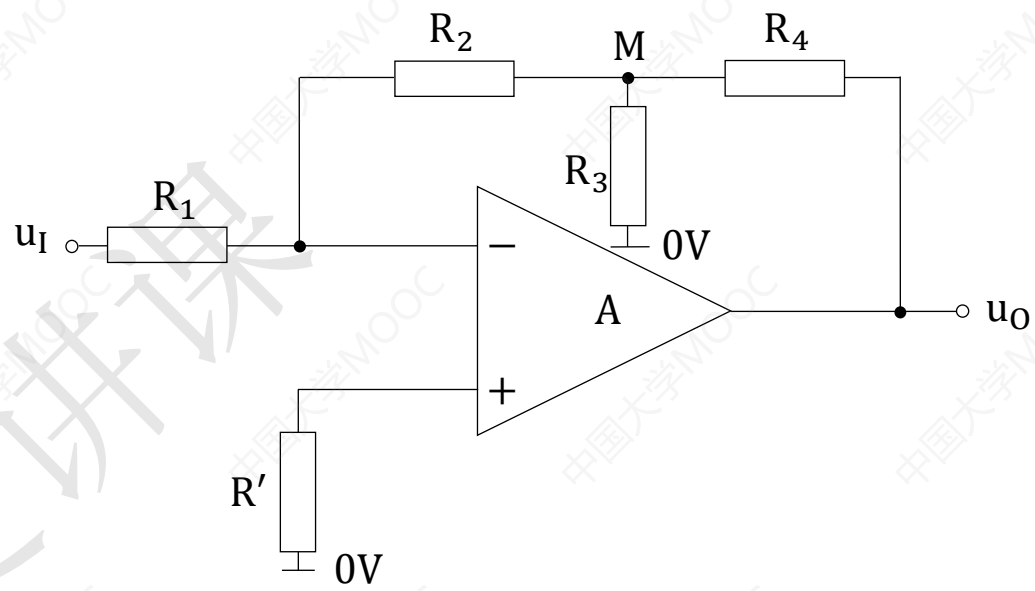
例2. 电路如图所示，已知u_I、R_1、R_2、R_3、R_4、R'，求u_O



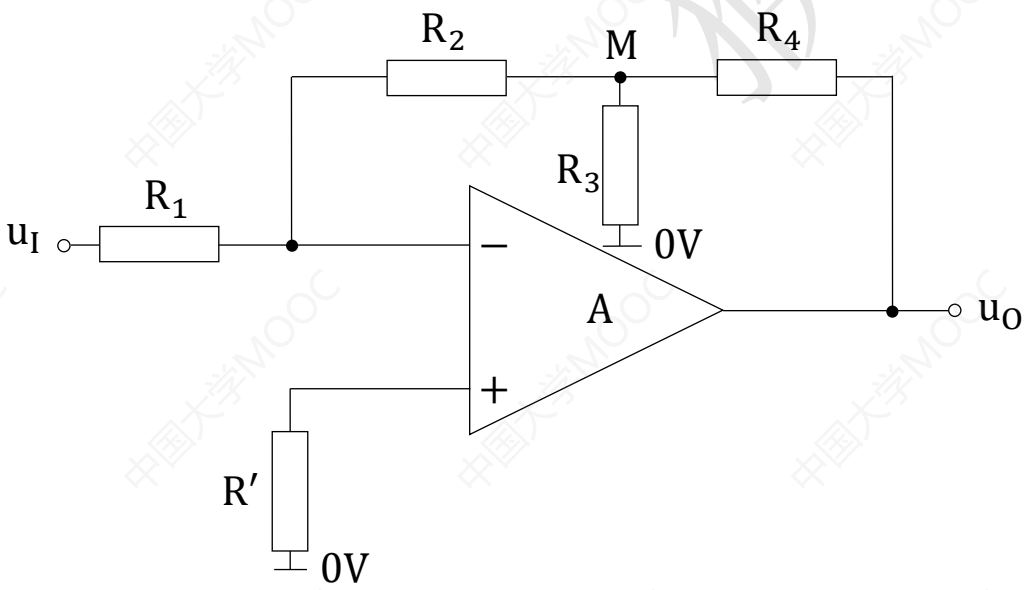
① 将各电压直接看做该点的电位，接地处电位为**0V**



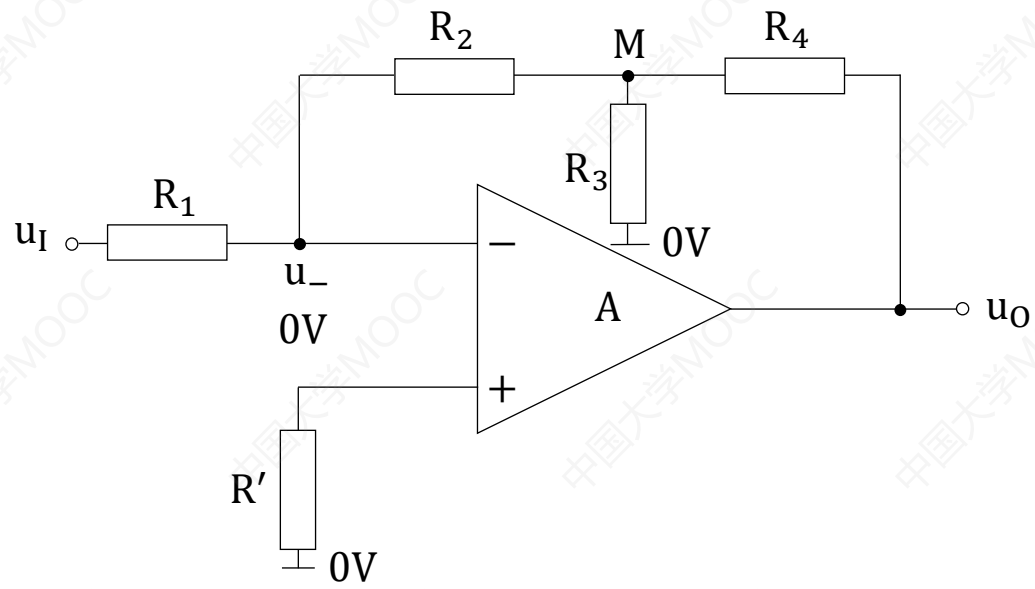
$\Longrightarrow$



② 在“**−**”号前面标上**u**₋，**u**₋ 处的电位 = **0V**



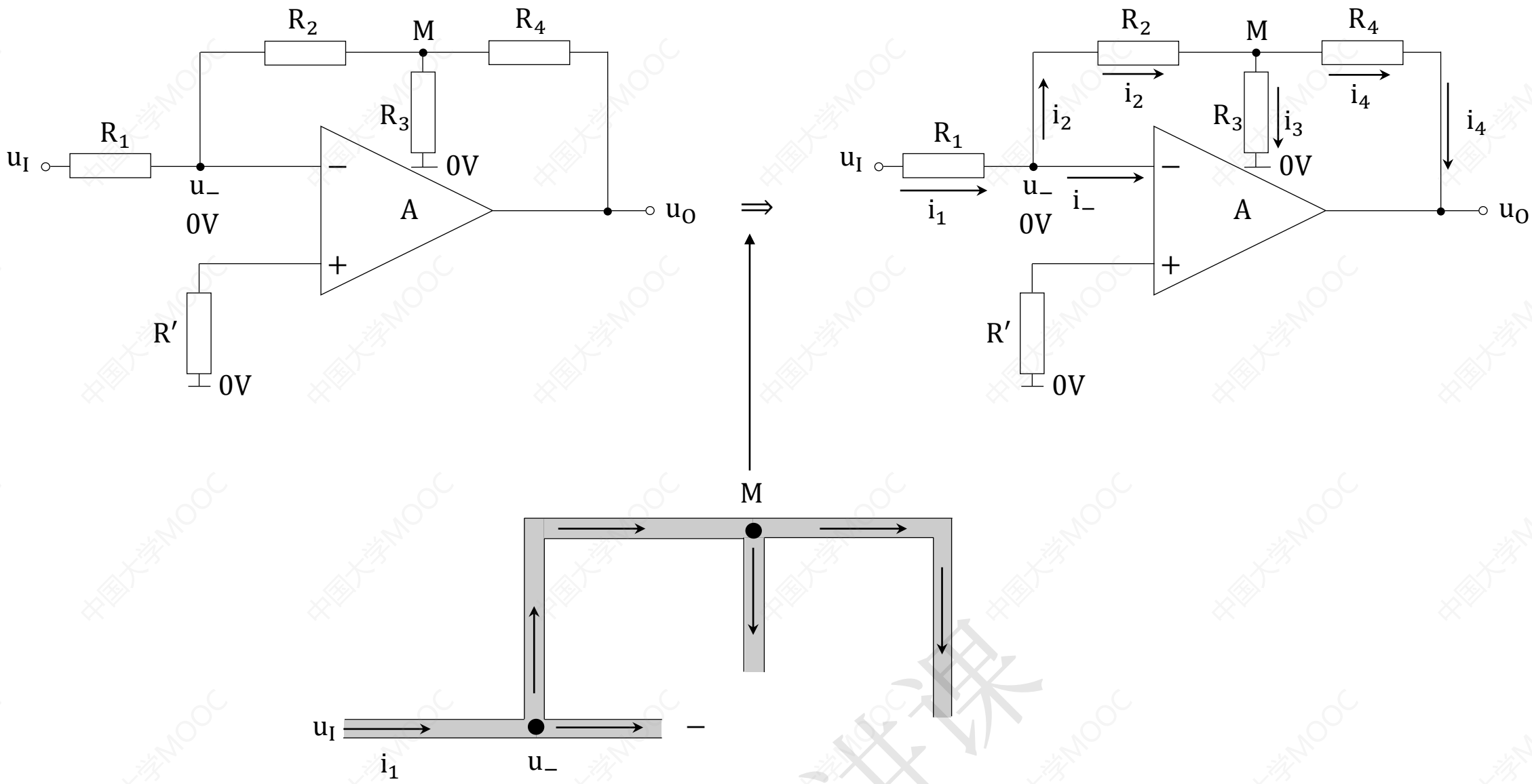
$\Longrightarrow$



③ 画出“−”输入端以及支路的电流方向

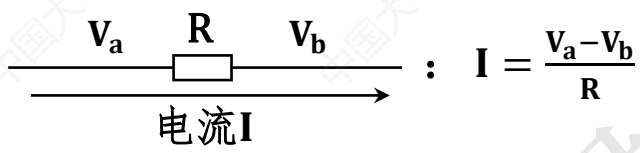
a、假设电流从输入电压处流入

b、将电流看做水流，将导线与电阻看做水管，画出水流方向即电流方向

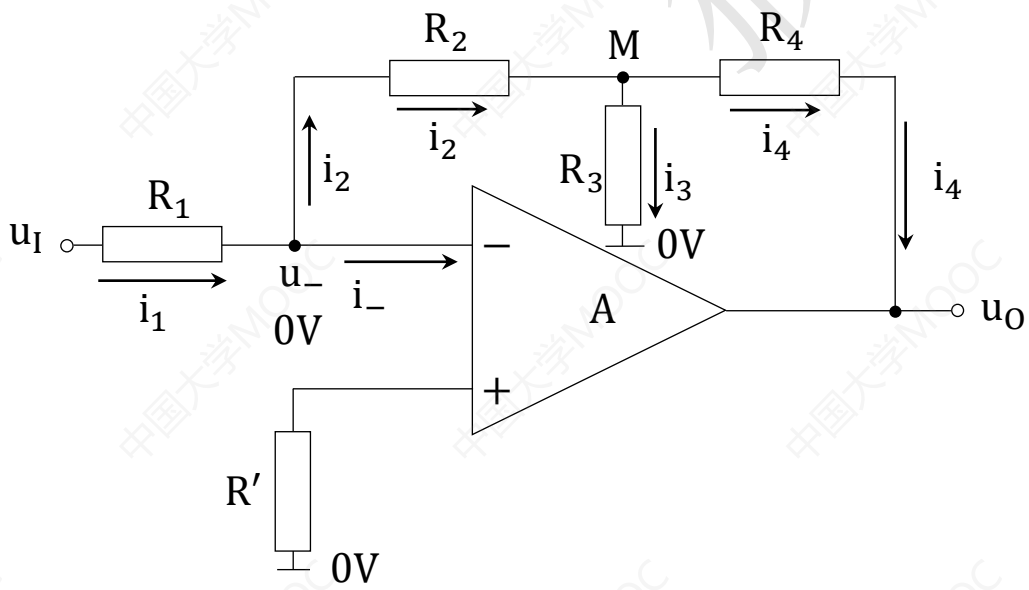


④ 分析 u_- 处、支路中分支节点处的电流大小关系

“−”号与 u_- 之间的电流为0



：$I=\frac{V_a-V_b}{R}$



u_-：$i_1=i_2$

$$\Rightarrow \frac{u_I-u_-}{R_1}=\frac{u_--u_M}{R_2}$$

$$\Rightarrow \frac{u_I-0V}{R_1}=\frac{0V-u_M}{R_2}$$

$$\Rightarrow \frac{u_I}{R_1}=\frac{-u_M}{R_2}$$

$$\Rightarrow u_M=-\frac{u_I}{R_1}\cdot R_2$$

M：$i_2=i_3+i_4$

$$\Rightarrow \frac{u_--u_M}{R_2}=\frac{u_M-0V}{R_3}+\frac{u_M-u_O}{R_4}$$

$$\Rightarrow \frac{0-\left(-\frac{u_I}{R_1}\cdot R_2\right)}{R_2}=\frac{-\frac{u_I}{R_1}\cdot R_2-0V}{R_3}+\frac{-\frac{u_I}{R_1}\cdot R_2-u_O}{R_4}$$

$$\Rightarrow \frac{u_I}{R_1}=-\frac{u_I}{R_1R_3}\cdot R_2+\left(-\frac{u_I}{R_1R_4}\cdot R_2\right)-\frac{u_O}{R_4}$$

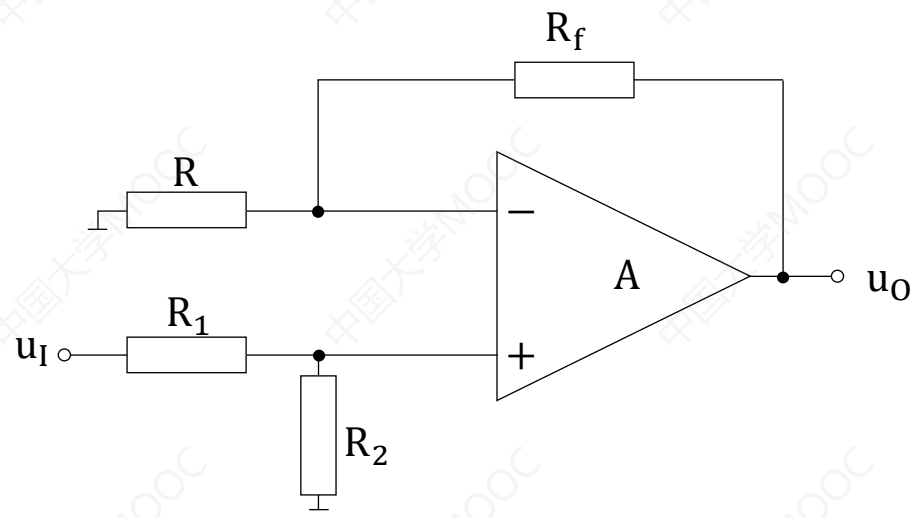
$$\Rightarrow \frac{u_O}{R_4}=-\frac{u_I}{R_1}-\frac{u_I}{R_1R_3}\cdot R_2-\frac{u_I}{R_1R_4}\cdot R_2$$

$$\Rightarrow u_O=-\frac{u_I}{R_1}\cdot R_4-\frac{u_I\,R_4}{R_1R_3}\cdot R_2-\frac{u_I}{R_1}\cdot R_2$$

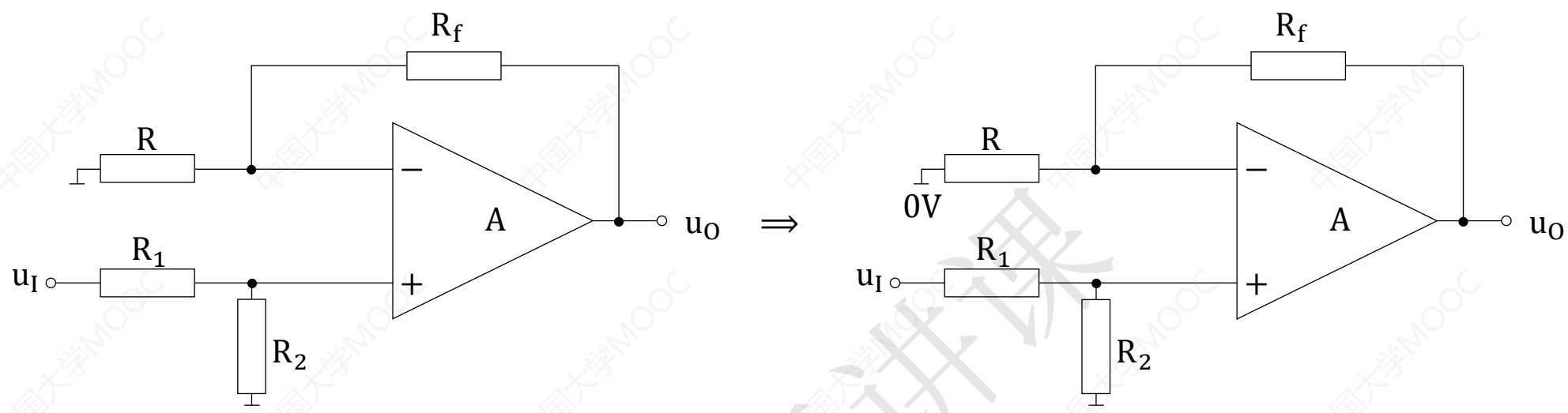
$$\Rightarrow u_O=-\frac{u_I}{R_1}\left(R_4+\frac{R_2R_4}{R_3}+R_2\right)$$

同相比例运算电路

例1. 电路如图所示，已知u_I、R、R_1、R_2、R_f，求u_O

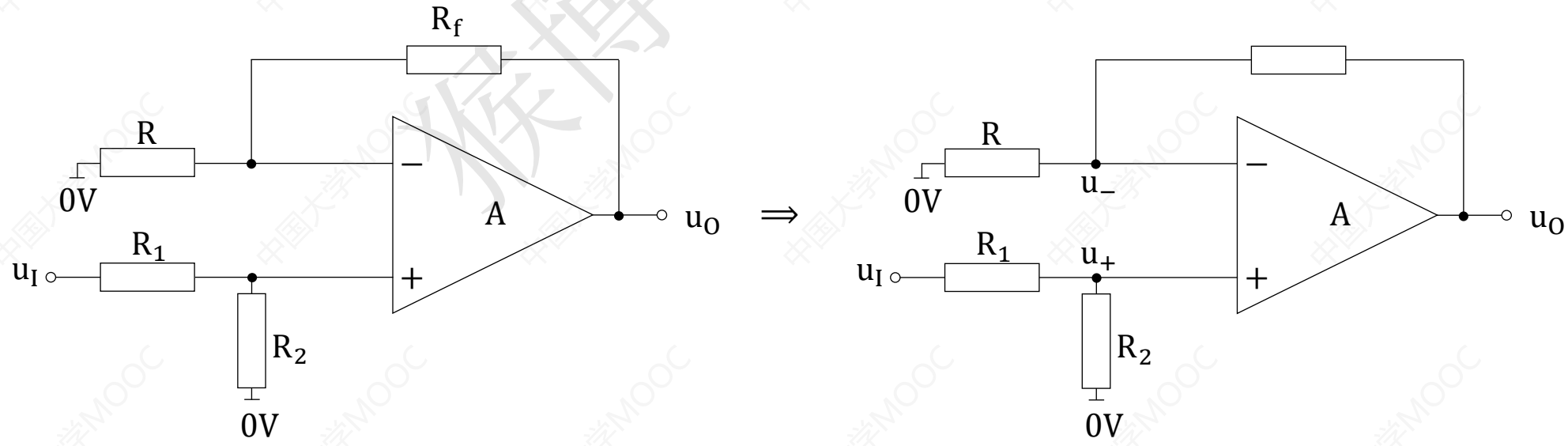


① 将各电压直接看做该点的电位，接地处电位为0V



② 在“+”号前面标上u_+，在“−”号前面标上u_-

且$u_- = u_+$

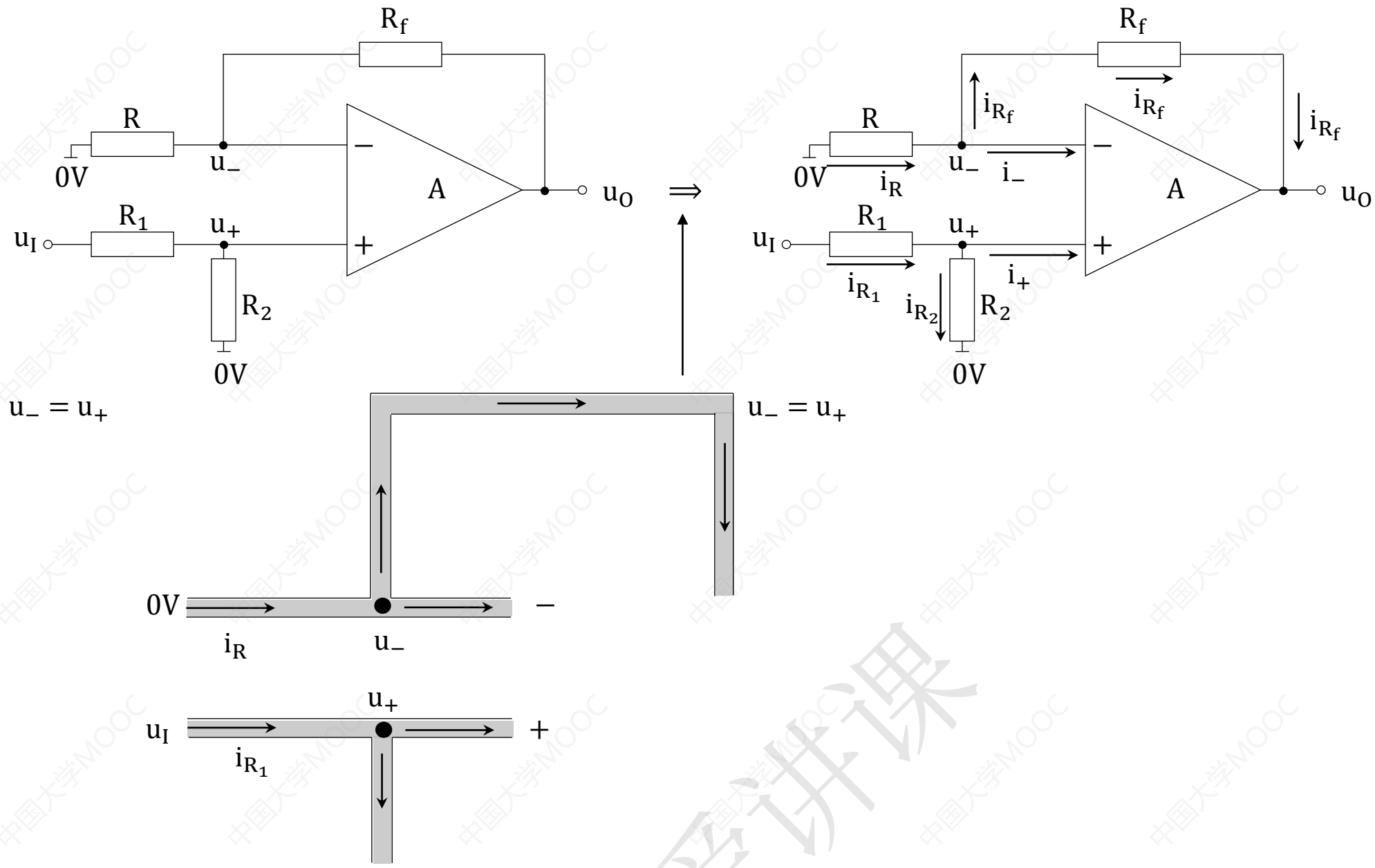


$u_- = u_+$

③ 画出“−”输入端以及支路的电流方向

a、假设电流从输入电压处流入

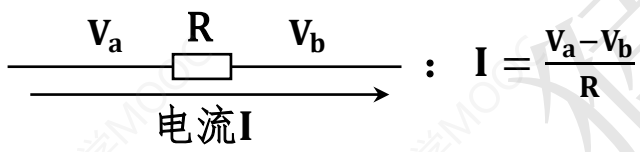
b、将电流看做水流，将导线与电阻看做水管，画出水流方向即电流方向



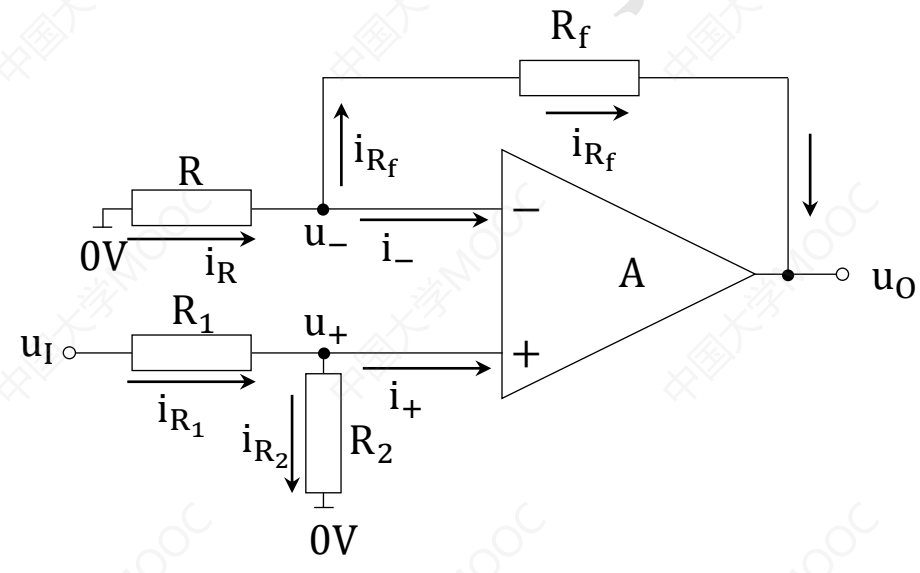
④ 分析 u_+ 处、u_- 处电流大小关系

“+”号与 u_+ 之间的电流为0

“−”号与 u_- 之间的电流为0



$$:\ I=\frac{V_a-V_b}{R}$$



$u_- = u_+ = \frac{R_2}{R_1+R_2}\cdot u_I$

u_+: $i_{R_1} = i_{R_2}$

$\Rightarrow \frac{u_I-u_+}{R_1} = \frac{u_+-0V}{R_2}$

$\Rightarrow \frac{u_I}{R_1} - \frac{u_+}{R_1} = \frac{u_+}{R_2}$

$\Rightarrow \frac{u_+}{R_1} + \frac{u_+}{R_2} = \frac{u_I}{R_1}$

$\Rightarrow u_+ = \frac{R_2}{R_1+R_2}\cdot u_I$

u_-: $i_R = i_{R_f}$

$\Rightarrow \frac{0V-u_-}{R} = \frac{u_--u_O}{R_f}$

$\Rightarrow -\frac{u_-}{R} = \frac{u_-}{R_f} - \frac{u_O}{R_f}$

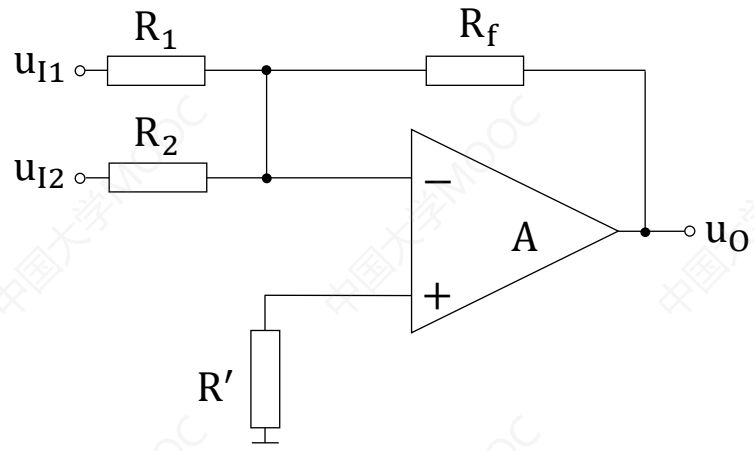
$\Rightarrow \frac{u_O}{R_f} = \frac{u_-}{R_f} + \frac{u_-}{R}$

$\Rightarrow u_O = \left(1+\frac{R_f}{R}\right)\cdot u_-$

$\Rightarrow u_O = \left(1+\frac{R_f}{R}\right)\cdot \frac{R_2}{R_1+R_2}\cdot u_I$

反相加法运算电路

例1. 电路如图所示，已知u_{I1}、u_{I2}、R_1、R_2、R'、R_f，求u_O

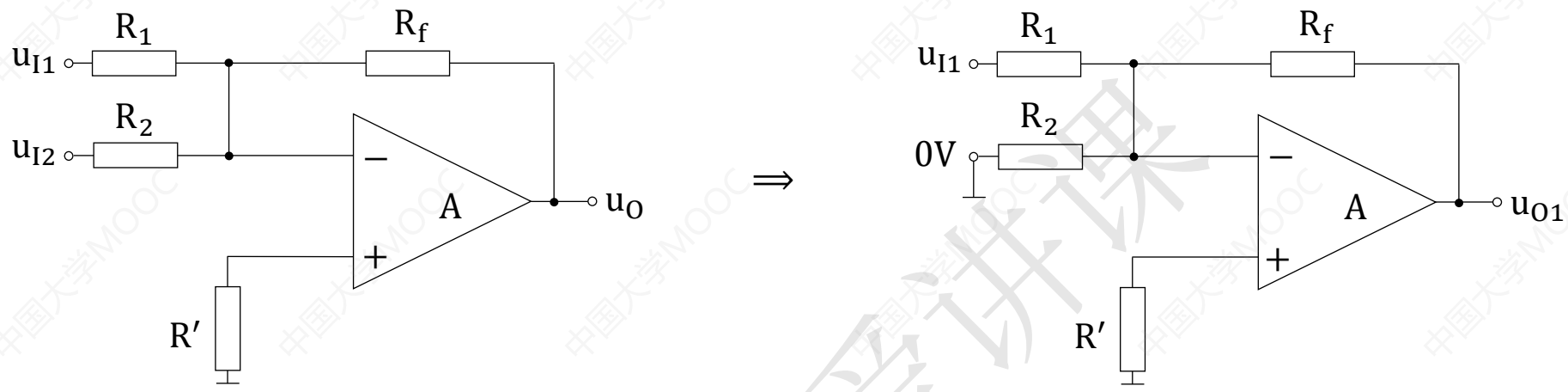


① 令输入电压$\mathbf{u_{I1}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O1}}$

令输入电压$\mathbf{u_{I2}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O2}}$

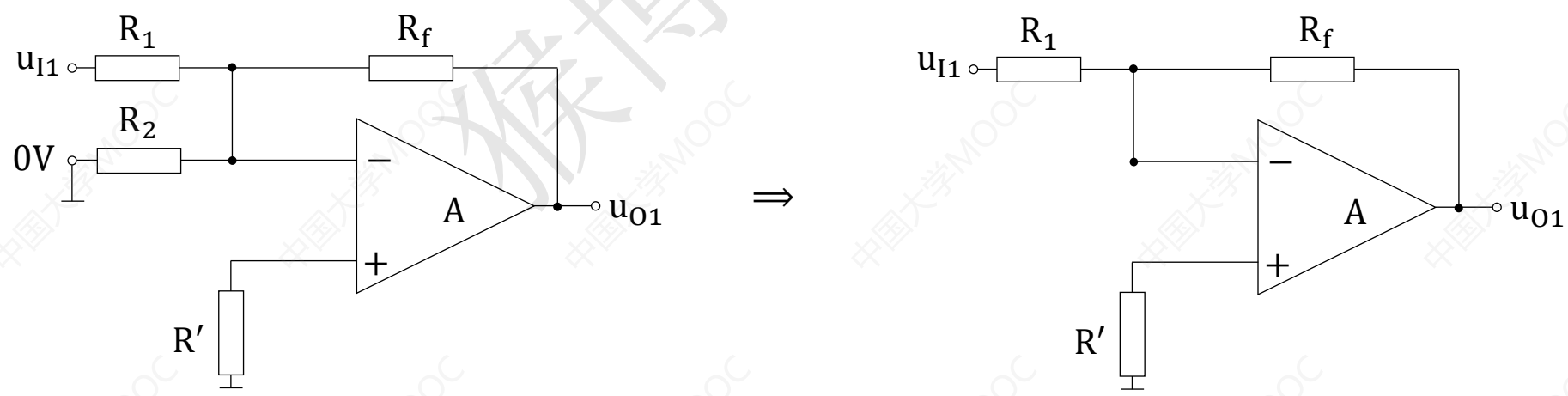
⋮　　⋮　　⋮

令输入电压$\mathbf{u_{In}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{On}}$

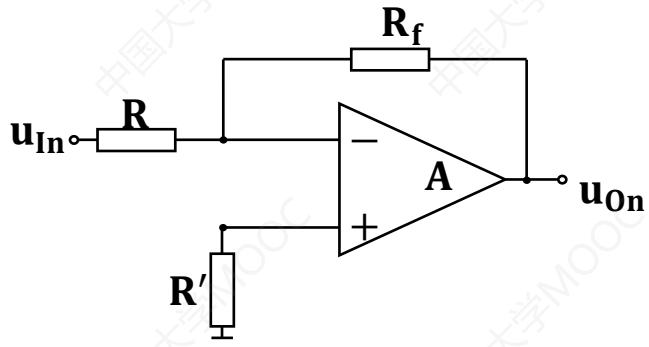


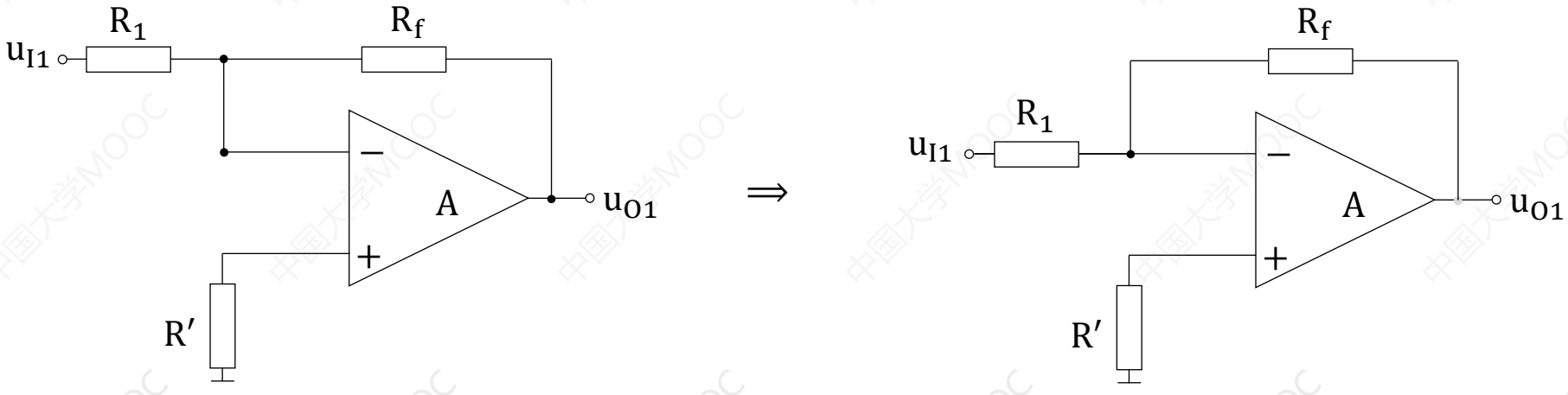
反相加法电路求输出电压$\mathbf{u_{On}}$：

a、去掉“−”端接“⊥”的电阻

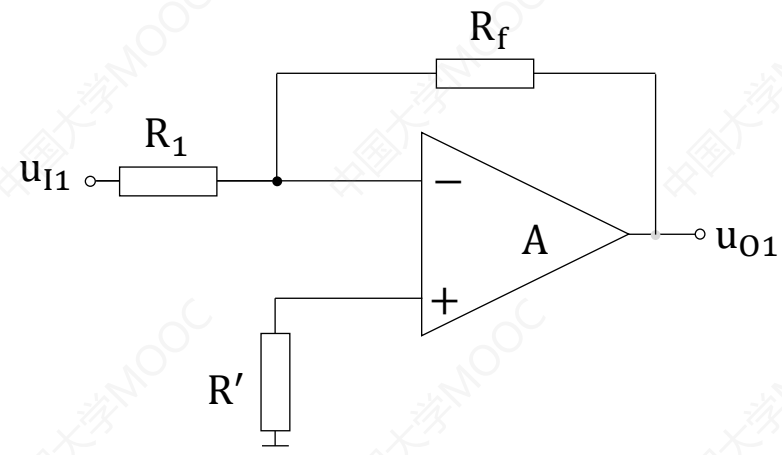


b、将剩下的电路图变成

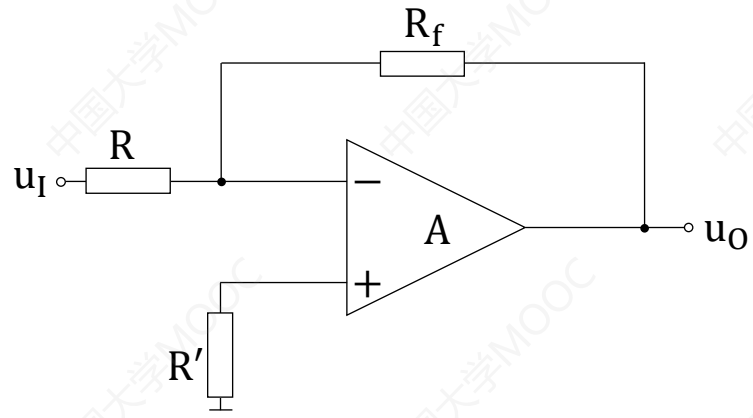




c、 运用反相比例运算电路的解题方法求解



$$u_{O1} = -\frac{R_f}{R_1} \cdot u_{I1}$$



$$u_O = -\frac{R_f}{R} \cdot u_I$$

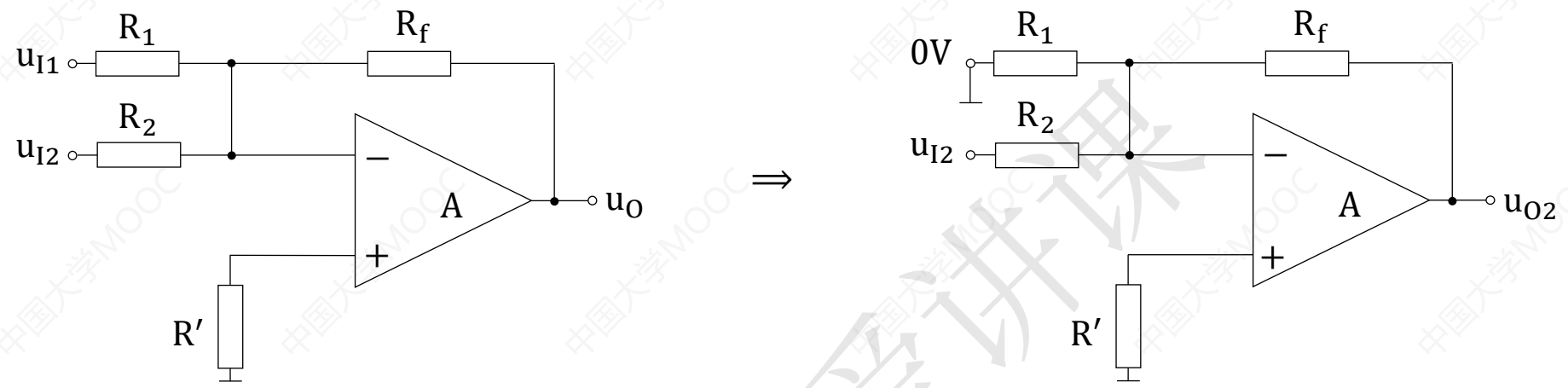
详见【集成运放应用】第1课【反相比例运算电路】

① 令输入电压$\mathbf{u_{I1}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O1}}$

令输入电压$\mathbf{u_{I2}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O2}}$

⋮ ⋮ ⋮

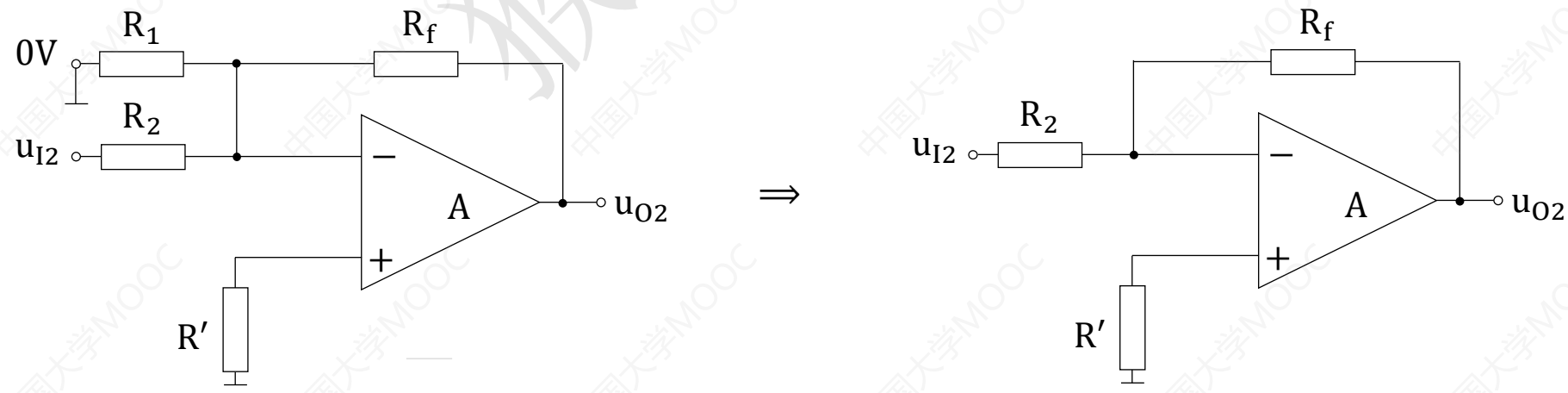
令输入电压$\mathbf{u_{In}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{On}}$



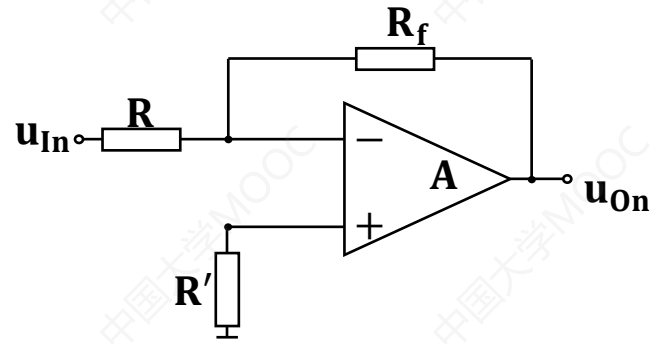
$$u_{O1} = -\frac{R_f}{R_1} \cdot u_{I1}$$

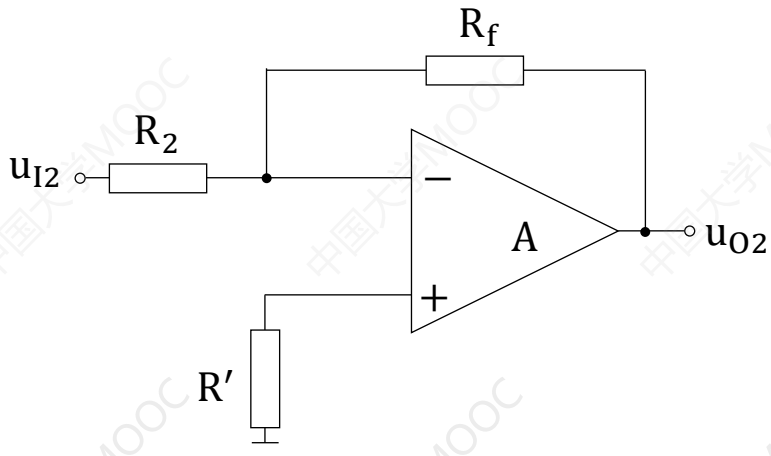
反相加法电路求输出电压$\mathbf{u_{On}}$：

a、去掉“−”端接“⊥”的电阻

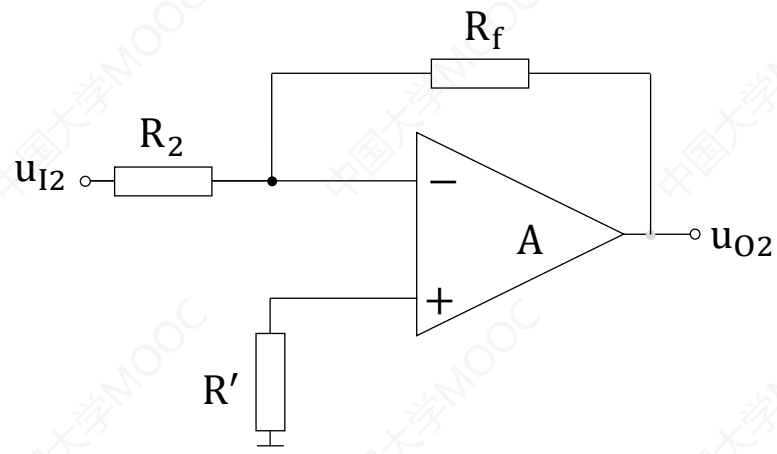


b、将剩下的电路图变成

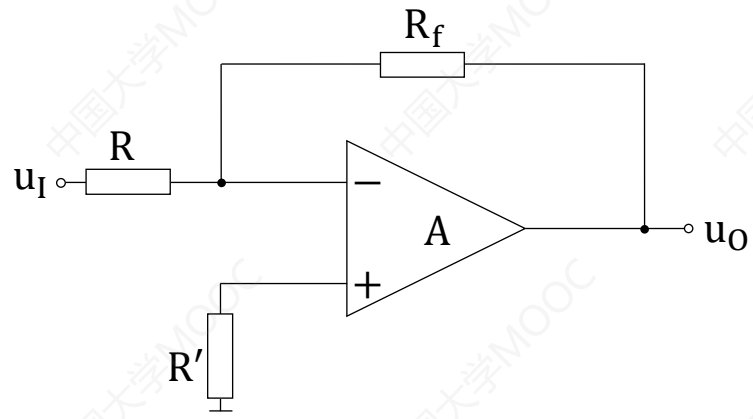




c、 运用反相比例运算电路的解题方法求解



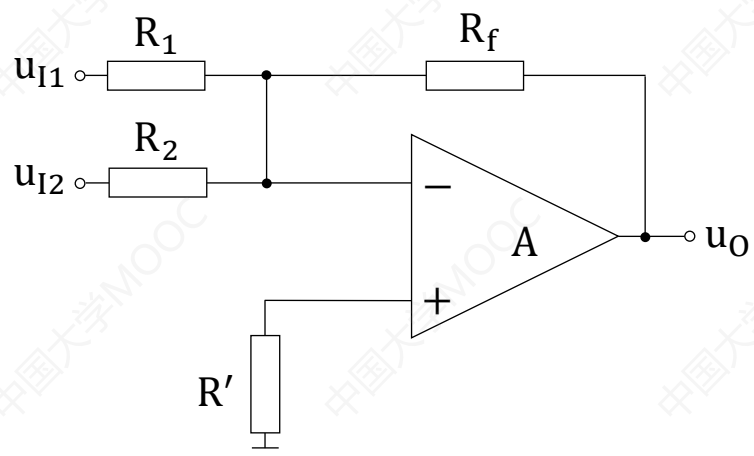
$$u_{O2} = -\frac{R_f}{R_2} \cdot u_{I2}$$



$$u_O = -\frac{R_f}{R} \cdot u_I$$

详见【集成运放应用】第1课【反相比例运算电路】

② $u_O = u_{O1} + u_{O2} + \cdots u_{On}$



$$u_{O1} = -\frac{R_f}{R_1} \cdot u_{I1} \qquad u_{O2} = -\frac{R_f}{R_2} \cdot u_{I2}$$

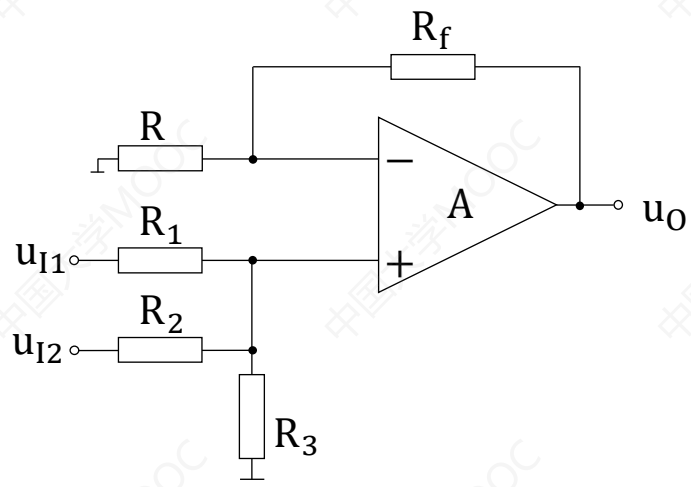
$$u_O = u_{O1} + u_{O2}$$

$$= -\frac{R_f}{R_1} \cdot u_{I1} + \left(-\frac{R_f}{R_2} \cdot u_{I2}\right)$$

$$= -\frac{R_f}{R_1} \cdot u_{I1} - \frac{R_f}{R_2} \cdot u_{I2}$$

同相加法运算电路

例1. 电路如图所示，已知u_{I1}、u_{I2}、R_1、R_2、R_3、R、R_f，求u_O

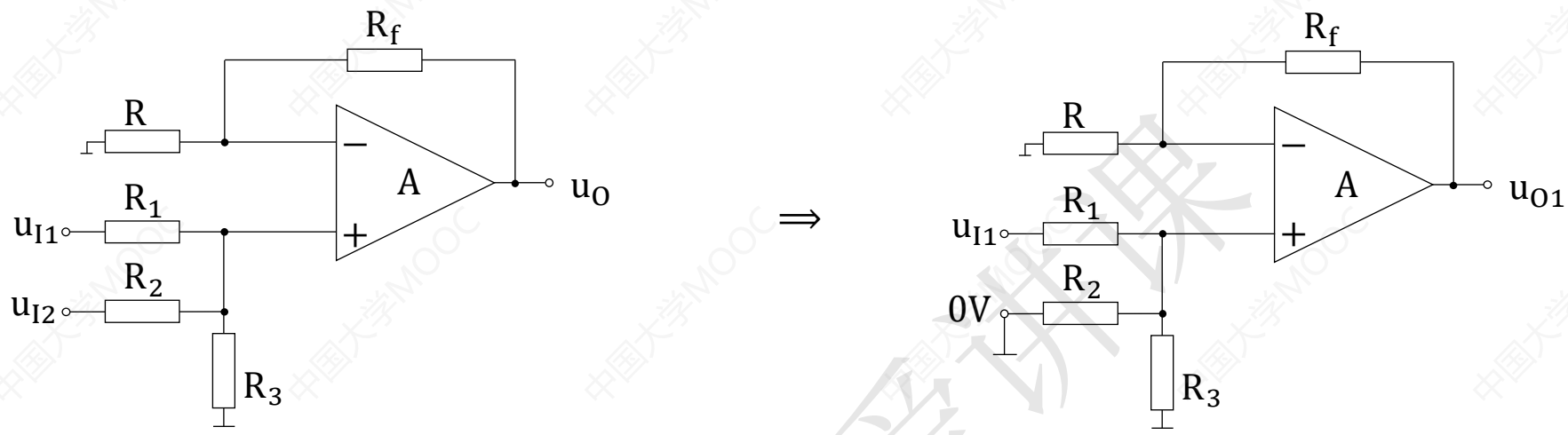


① 令输入电压u_{I1}不变，其他输入电压为0，求得此时的输出电压u_{O1}

令输入电压u_{I2}不变，其他输入电压为0，求得此时的输出电压u_{O2}

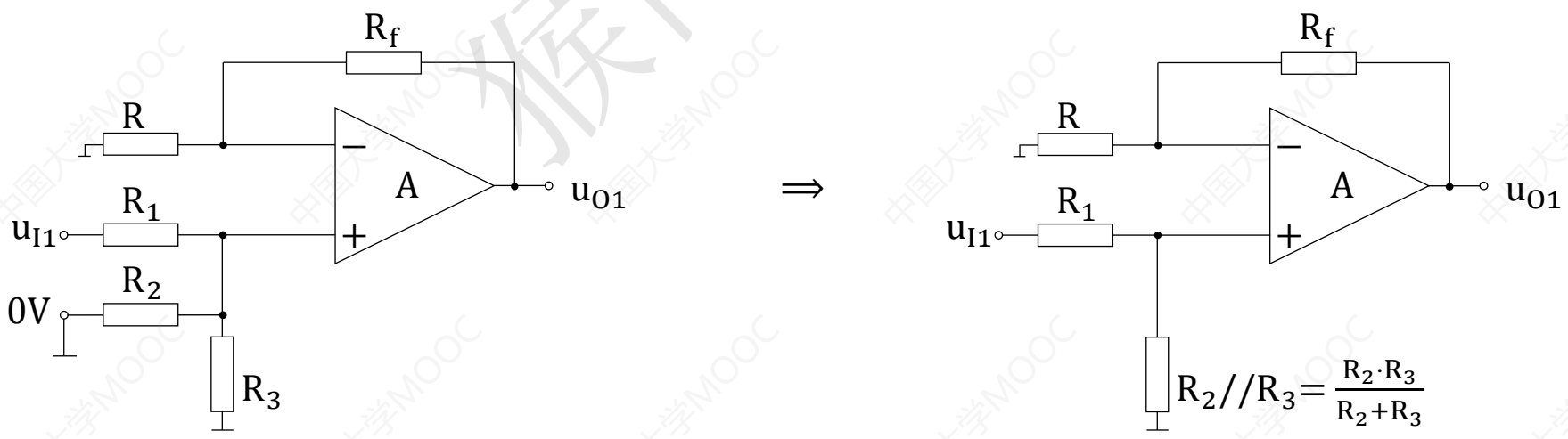
⋮　　⋮　　⋮

令输入电压u_{In}不变，其他输入电压为0，求得此时的输出电压u_{On}

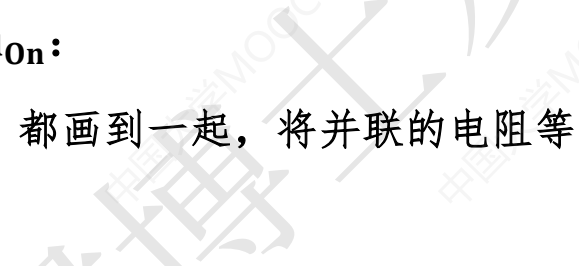


同相加法电路求输出电压u_{On}：

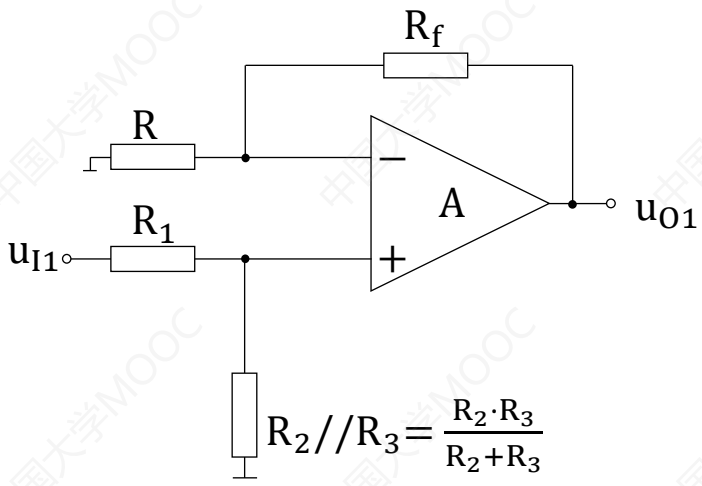
a、将“+”号端的“⊥”都画到一起，将并联的电阻等效为一个电阻

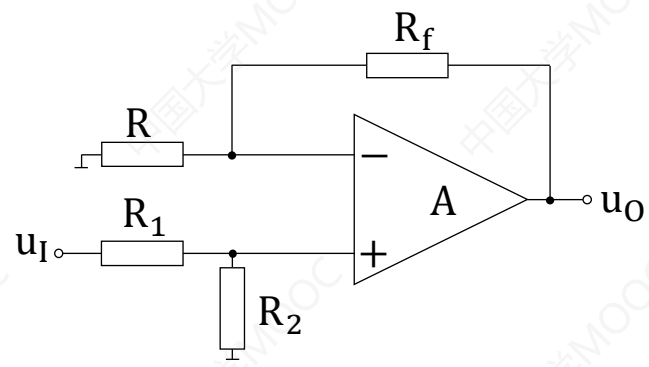


b、将剩下的电路图变成



c、 运用同相比例运算电路的解题方法求解





$u_O=\left(1+\frac{R_f}{R}\right)\frac{R_2}{R_1+R_2}\cdot u_I$

详见【集成运放应用】第**2**课【同相比例运算电路】

$$u_{O1}=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_2\cdot R_3}{R_2+R_3}}{R_1+\frac{R_2\cdot R_3}{R_2+R_3}}\cdot u_{I1}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_2\cdot R_3}{R_2+R_3}}{\frac{R_1(R_2+R_3)}{R_2+R_3}+\frac{R_2\cdot R_3}{R_2+R_3}}\cdot u_{I1}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_2\cdot R_3}{R_2+R_3}}{\frac{R_1R_2+R_1R_3}{R_2+R_3}+\frac{R_2\cdot R_3}{R_2+R_3}}\cdot u_{I1}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_2\cdot R_3}{R_2+R_3}}{\frac{R_1R_2+R_2R_3+R_1R_3}{R_2+R_3}}\cdot u_{I1}$$

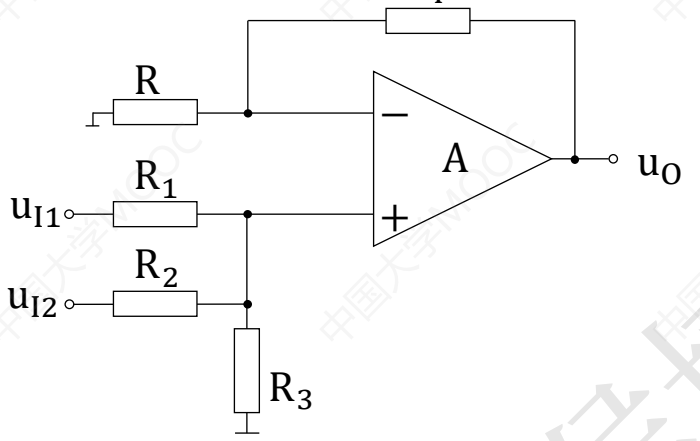
$$=\left(1+\frac{R_f}{R}\right)\frac{R_2R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I1}$$

① 令输入电压$\mathbf{u_{I1}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O1}}$

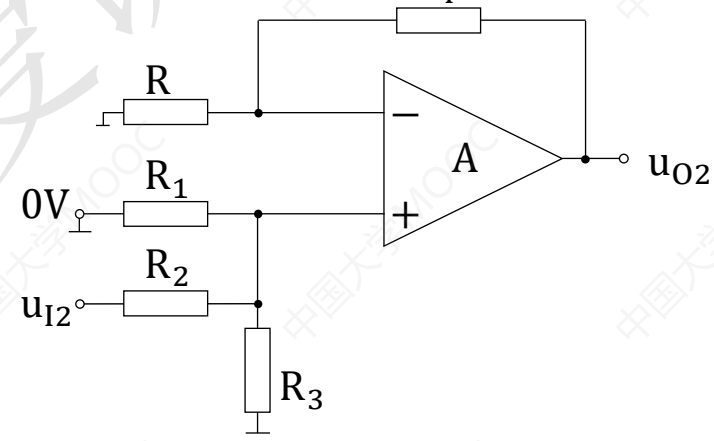
令输入电压$\mathbf{u_{I2}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O2}}$

⋮ ⋮ ⋮

令输入电压$\mathbf{u_{In}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{On}}$



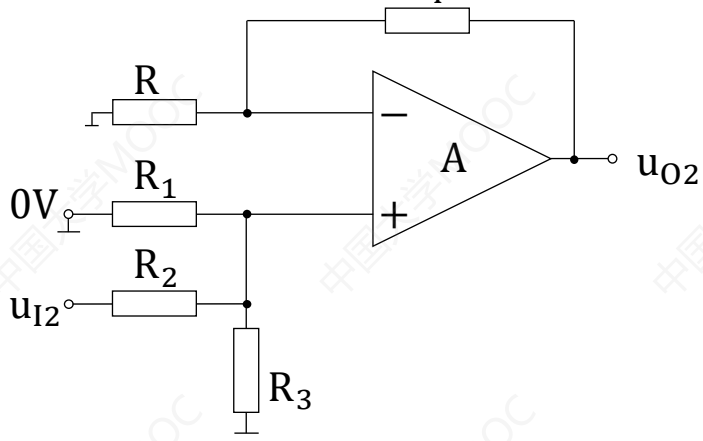
⟹



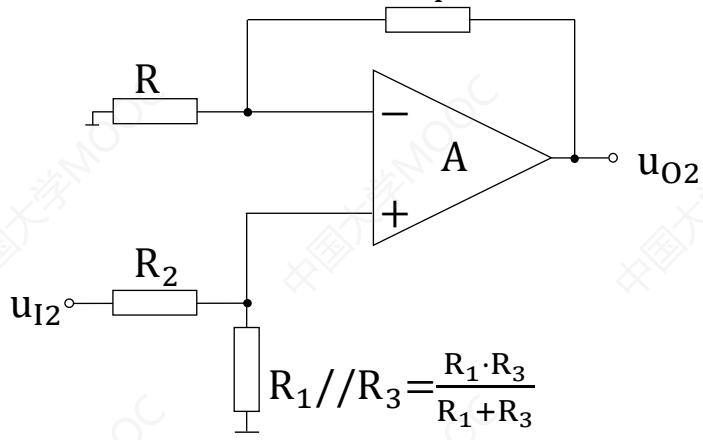
$$u_{O1}=\left(1+\frac{R_f}{R}\right)\frac{R_2R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I1}$$

同相加法电路求输出电压$\mathbf{u_{On}}$：

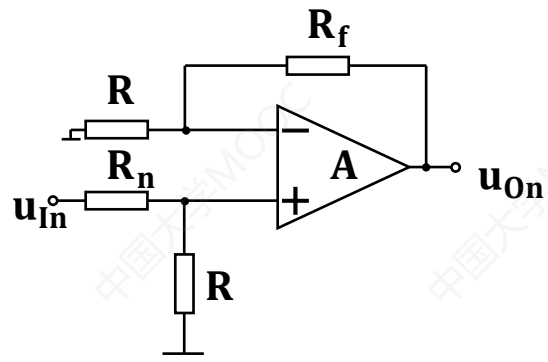
a、 将“+”号端的“⊥”都画到一起，将并联的电阻等效为一个电阻

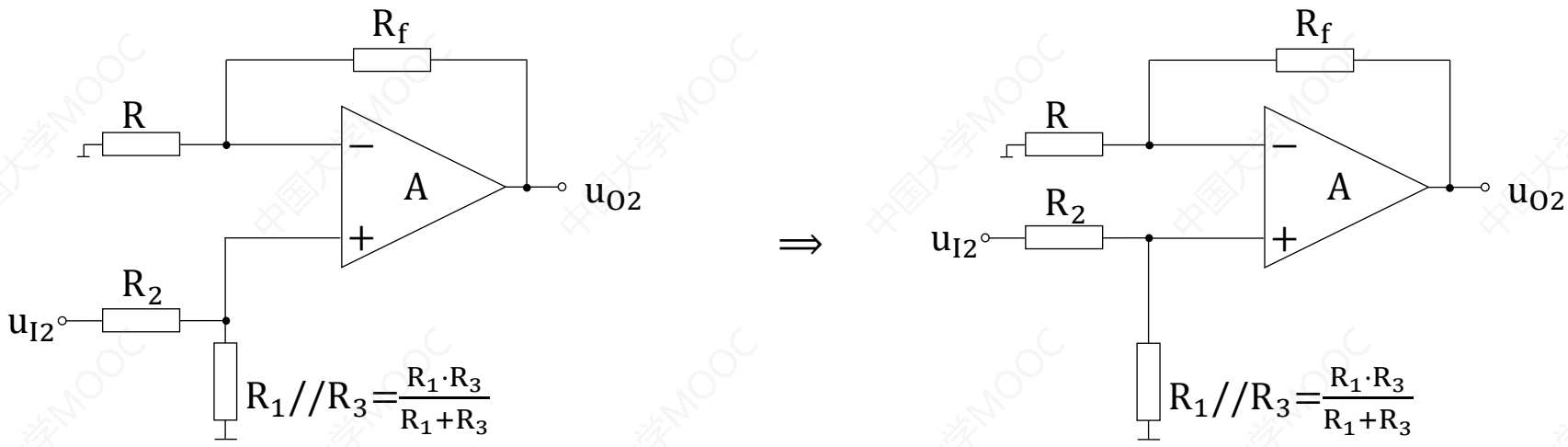


⟹

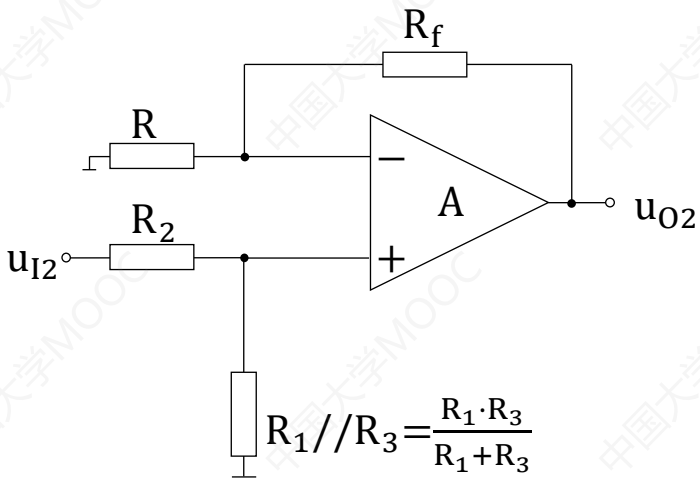


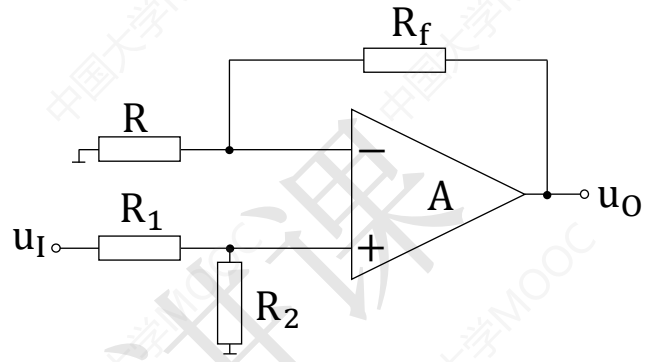
b、将剩下的电路图变成





c、 运用同相比例运算电路的解题方法求解





详见【集成运放应用】第**2**课【同相比例运算电路】

$$u_{O2}=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_1\cdot R_3}{R_1+R_3}}{R_2+\frac{R_1\cdot R_3}{R_1+R_3}}\cdot u_{I2}$$

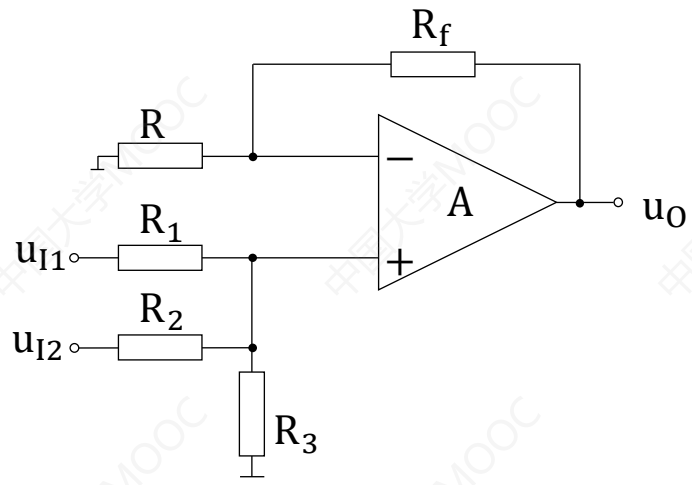
$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_1\cdot R_3}{R_1+R_3}}{\frac{R_2(R_1+R_3)}{R_1+R_3}+\frac{R_1\cdot R_3}{R_1+R_3}}\cdot u_{I2}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_1\cdot R_3}{R_1+R_3}}{\frac{R_1R_2+R_2R_3}{R_1+R_3}+\frac{R_1\cdot R_3}{R_1+R_3}}\cdot u_{I2}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{\frac{R_1\cdot R_3}{R_1+R_3}}{\frac{R_1R_2+R_2R_3+R_1R_3}{R_1+R_3}}\cdot u_{I2}$$

$$=\left(1+\frac{R_f}{R}\right)\frac{R_1R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I2}$$

② $u_O=u_{O1}+u_{O2}+\cdots u_{On}$



$$u_{O1}=\left(1+\frac{R_f}{R}\right)\frac{R_2R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I1}$$

$$u_{O2}=\left(1+\frac{R_f}{R}\right)\frac{R_1R_3}{R_1R_2+R_1R_3+R_2R_3}\cdot u_{I2}$$

$$u_O=u_{O1}+u_{O2}$$

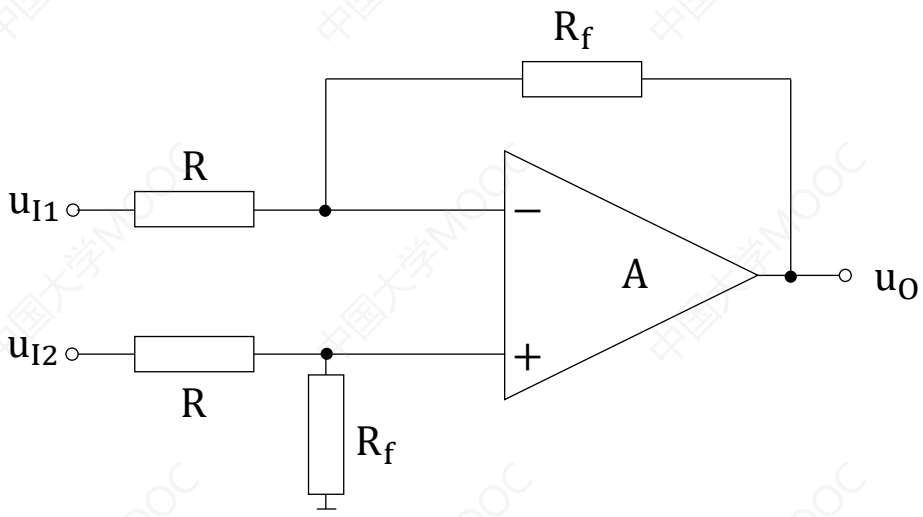
$$=\left(1+\frac{R_f}{R}\right)\frac{R_2R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I1}+\left(1+\frac{R_f}{R}\right)\frac{R_1R_3}{R_1R_2+R_1R_3+R_2R_3}\cdot u_{I2}$$

$$=\frac{R+R_f}{R}\cdot\frac{R_2R_3}{R_1R_2+R_2R_3+R_1R_3}\cdot u_{I1}+\frac{R+R_f}{R}\cdot\frac{R_1R_3}{R_1R_2+R_1R_3+R_2R_3}\cdot u_{I2}$$

$$=\frac{R_2R_3(R+R_f)u_{I1}}{R(R_1R_2+R_2R_3+R_1R_3)}+\frac{R_1R_3(R+R_f)u_{I2}}{R(R_1R_2+R_2R_3+R_1R_3)}=\frac{R_3(R+R_f)}{R(R_1R_2+R_1R_3+R_2R_3)}(R_2u_{I1}+R_1u_{I2})$$

减法运算电路

例1. 电路如图所示，已知u_{I1}、u_{I2}、R、R_f，求u_O

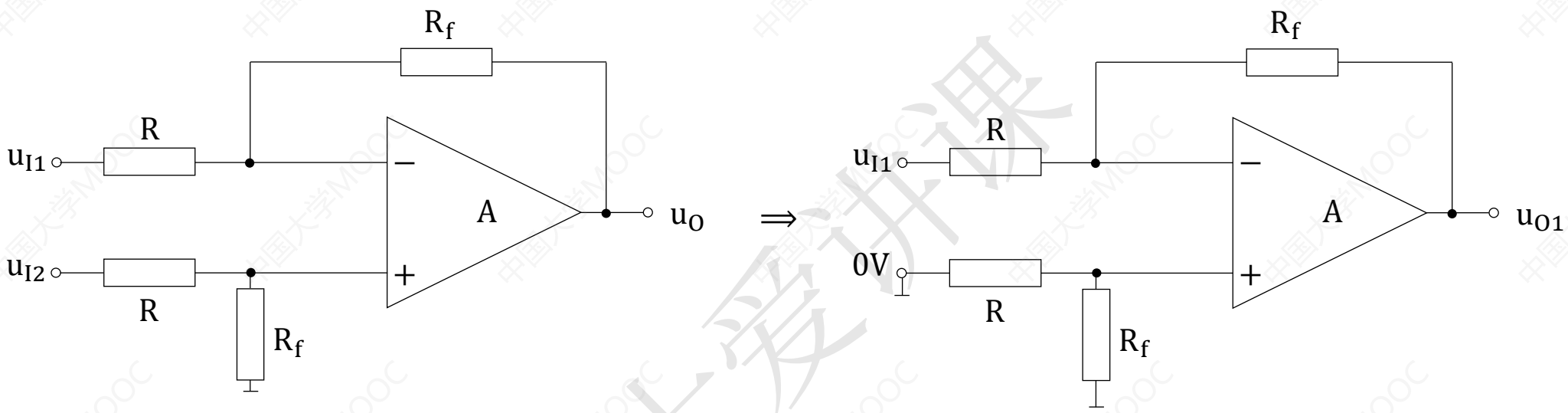


① 令输入电压$\mathbf{u_{I1}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O1}}$

令输入电压$\mathbf{u_{I2}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O2}}$

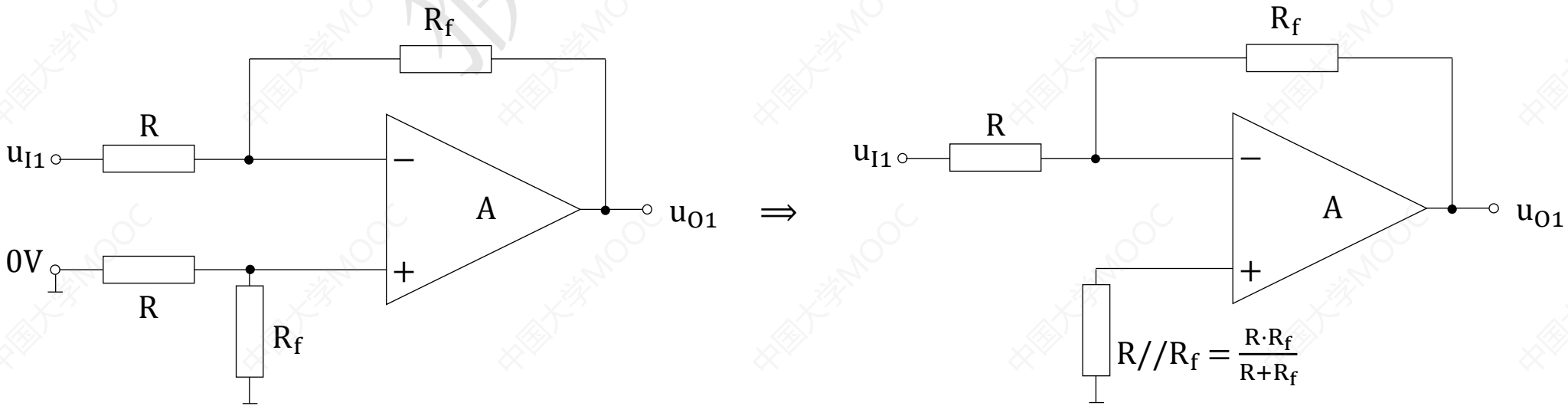
⋮　　⋮　　⋮

令输入电压$\mathbf{u_{In}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{On}}$

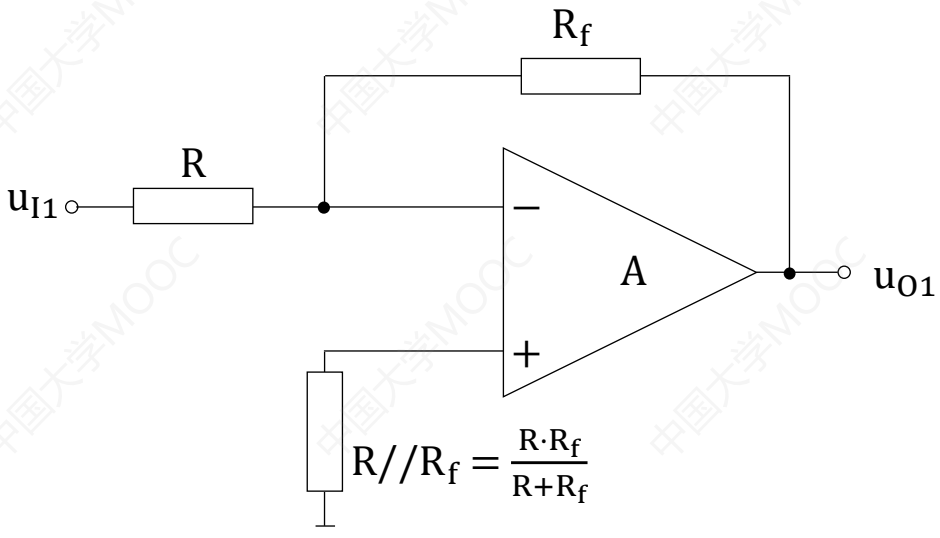


减法电路求输出电压$\mathbf{u_{On}}$：

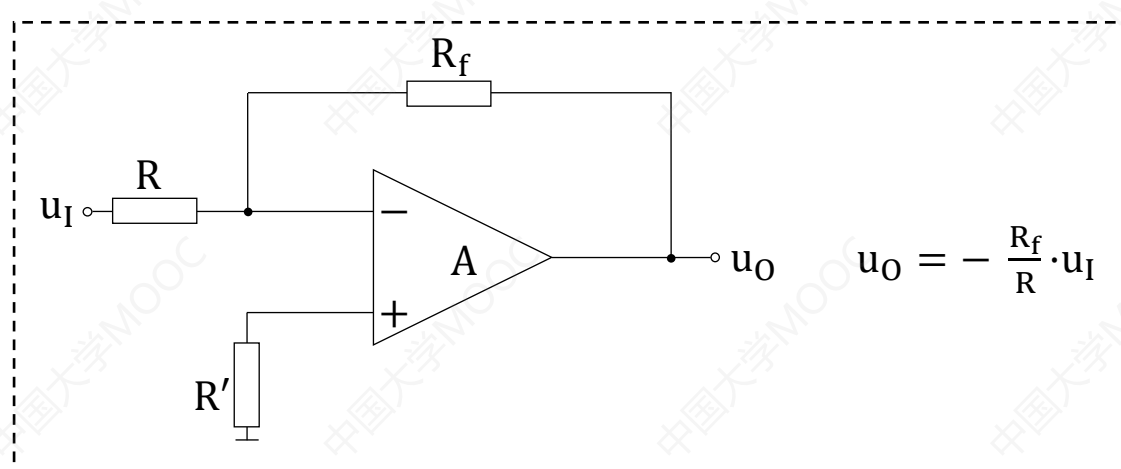
a、将“+”号端的“⊥”都画到一起，将并联的电阻等效为一个电阻



b、运用反相比例或同相比例运算电路的解题方法求解



$u_{O1} = -\frac{R_f}{R} \cdot u_{I1}$



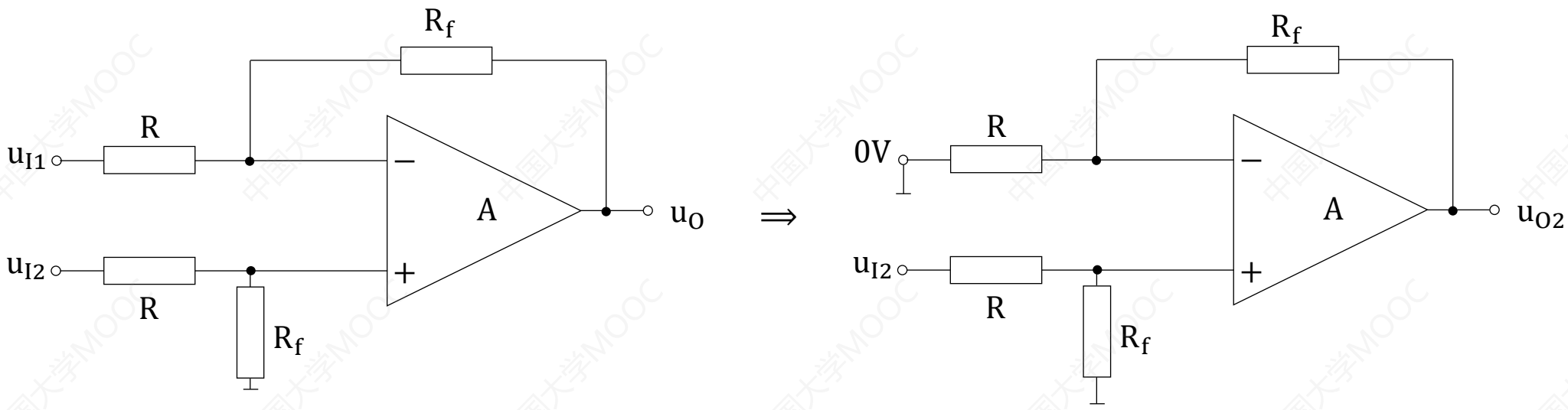
详见【集成运放应用】第1课【反相比例运算电路】

① 令输入电压$\mathbf{u_{I1}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O1}}$

令输入电压$\mathbf{u_{I2}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{O2}}$

⋮　　⋮　　⋮

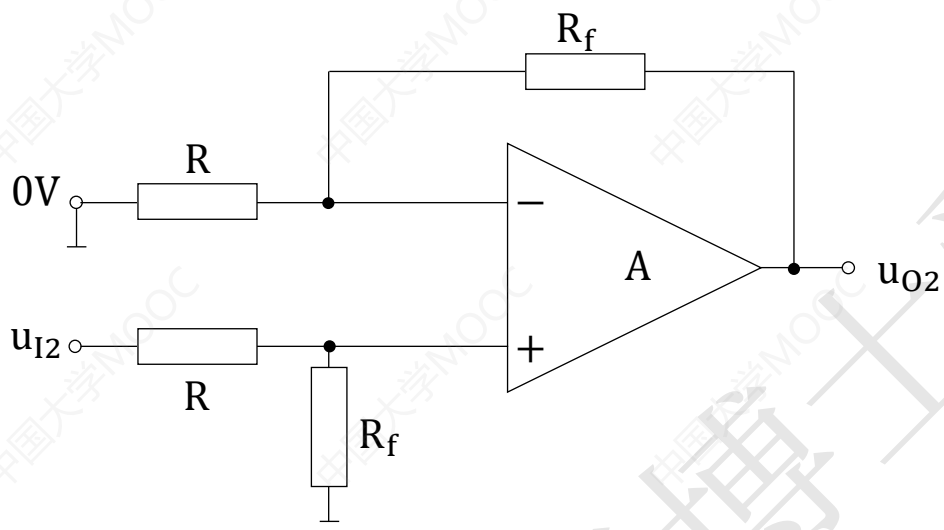
令输入电压$\mathbf{u_{In}}$不变，其他输入电压为0，求得此时的输出电压$\mathbf{u_{On}}$



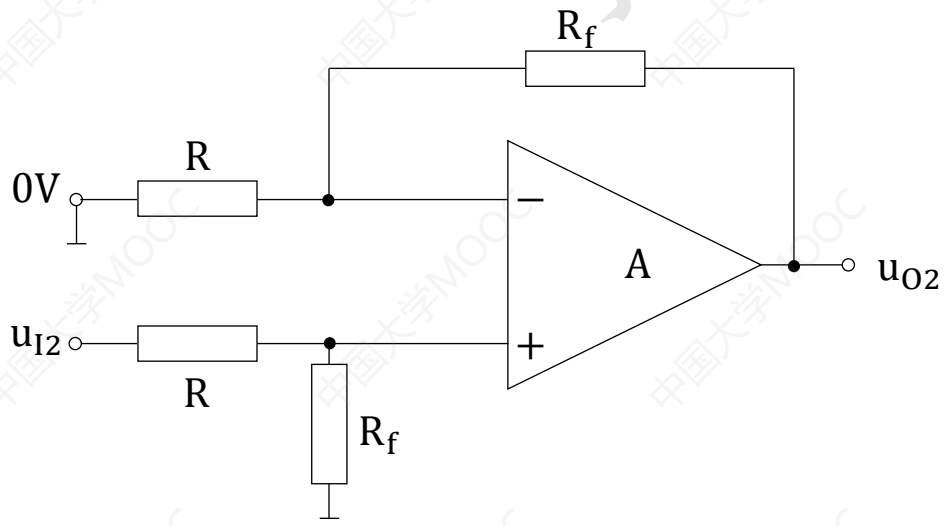
$$u_{O1} = -\frac{R_f}{R} \cdot u_{I1}$$

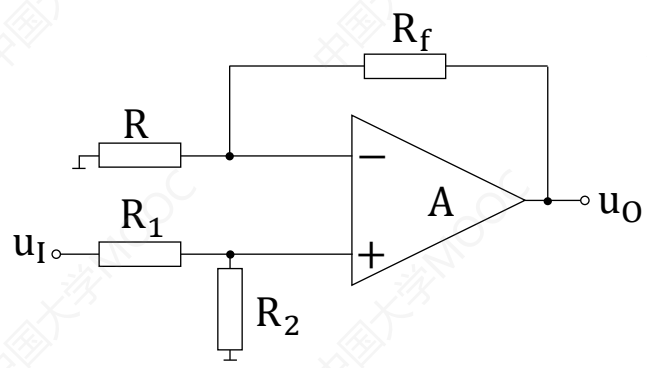
减法电路求输出电压$\mathbf{u_{On}}$：

a、将“+”号端的“⊥”都画到一起，将并联的电阻等效为一个电阻



b、运用反相比例或同相比例运算电路的解题方法求解



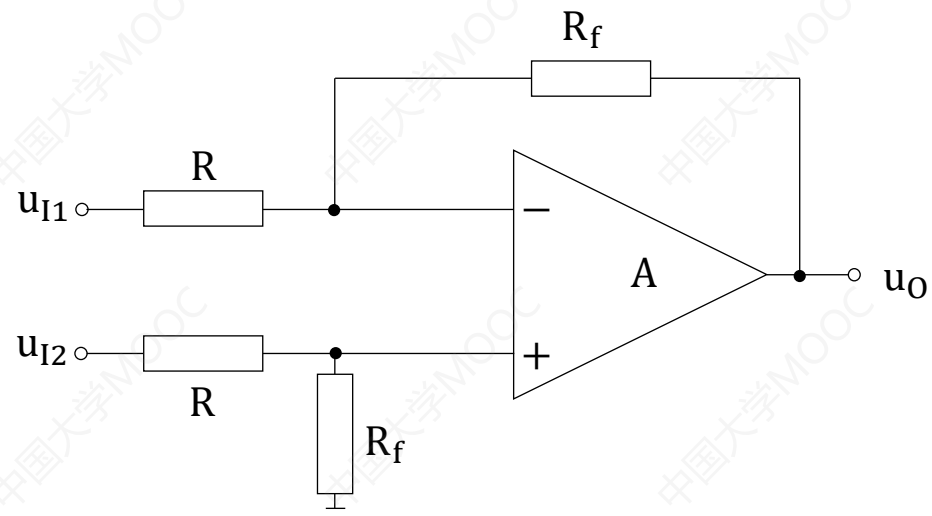


$$u_O = \left(1 + \frac{R_f}{R}\right) \frac{R_2}{R_1 + R_2} \cdot u_I$$

详见【集成运放应用】第2课【同相比例运算电路】

$$u_{O2} = \left(1 + \frac{R_f}{R}\right) \frac{R_f}{R + R_f} \cdot u_{I2}$$

② $\mathbf{u_O = u_{O1} + u_{O2} + \cdots + u_{On}}$



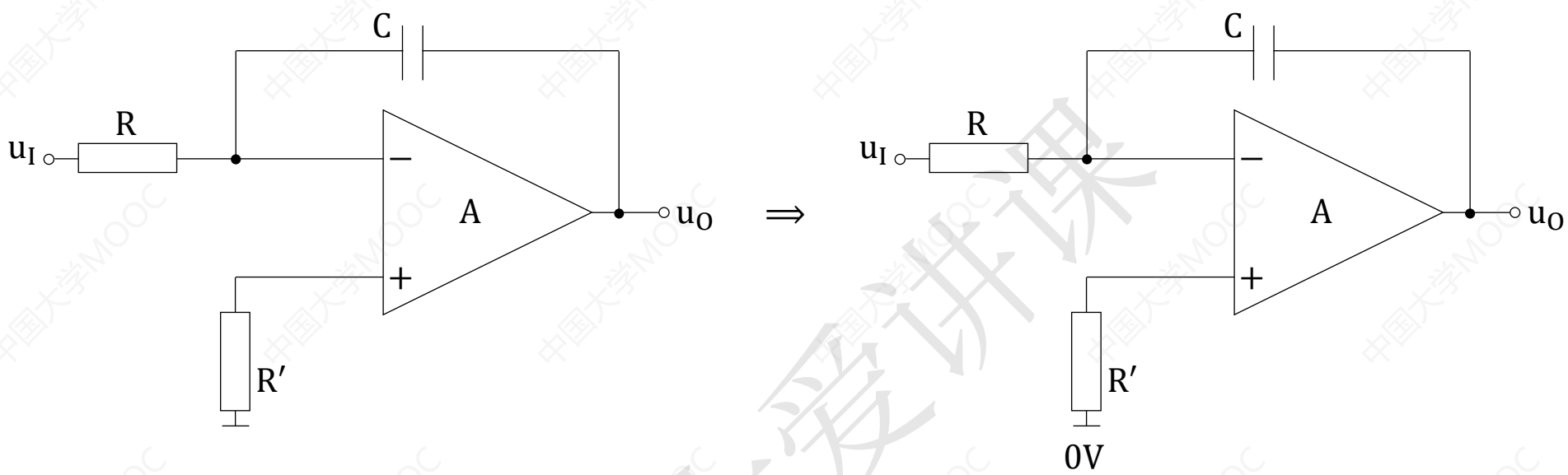
$$u_{O1} = -\frac{R_f}{R}\cdot u_{I1} \qquad u_{O2} = \left(1+\frac{R_f}{R}\right)\frac{R_f}{R+R_f}\cdot u_{I2}$$

$$\begin{aligned} u_O &= u_{O1} + u_{O2} \\ &= -\frac{R_f}{R}\cdot u_{I1} + \left(1+\frac{R_f}{R}\right)\frac{R_f}{R+R_f}\cdot u_{I2} \\ &= -\frac{R_f}{R}\cdot u_{I1} + \frac{R+R_f}{R}\cdot\frac{R_f}{R+R_f}\cdot u_{I2} \\ &= -\frac{R_f}{R}\cdot u_{I1} + \frac{R_f}{R}\cdot u_{I2} \\ &= \frac{R_f}{R}\cdot(u_{I2} - u_{I1}) \end{aligned}$$

带电容的集成运放电路

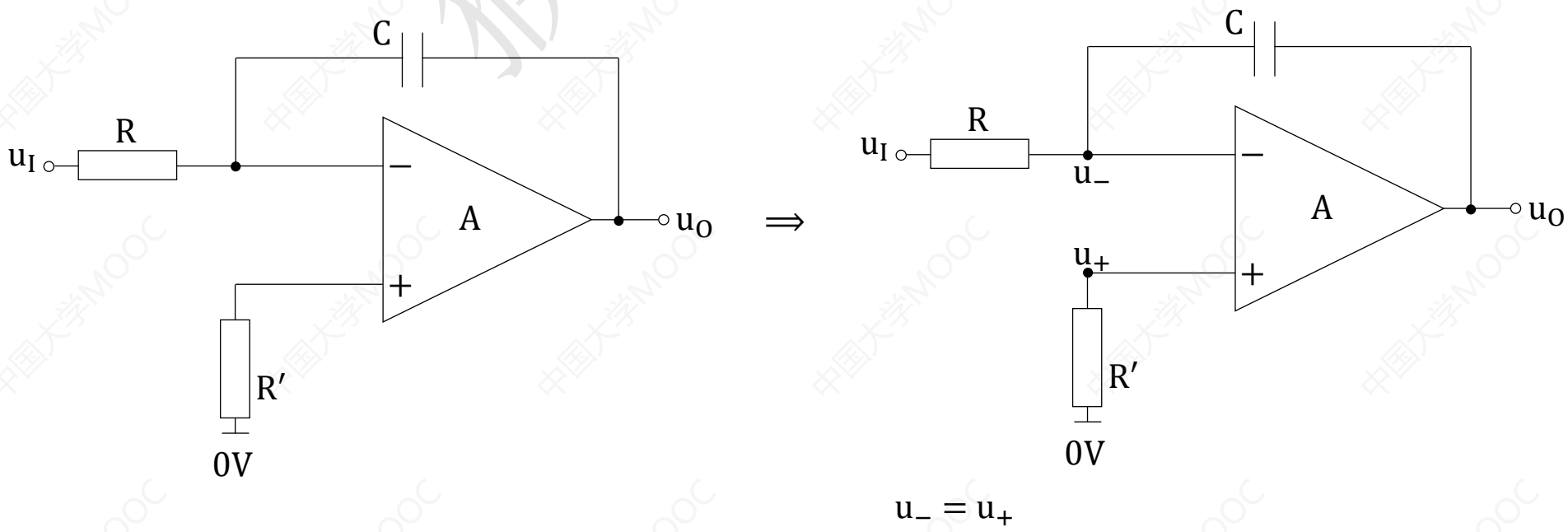
例1. 电路如图所示，已知u_I、R、R′、C，求u_O

① 将各电压直接看做该点的电位，接地处电位为0V



② 在“+”号前面标上u_+，在“−”号前面标上u_-

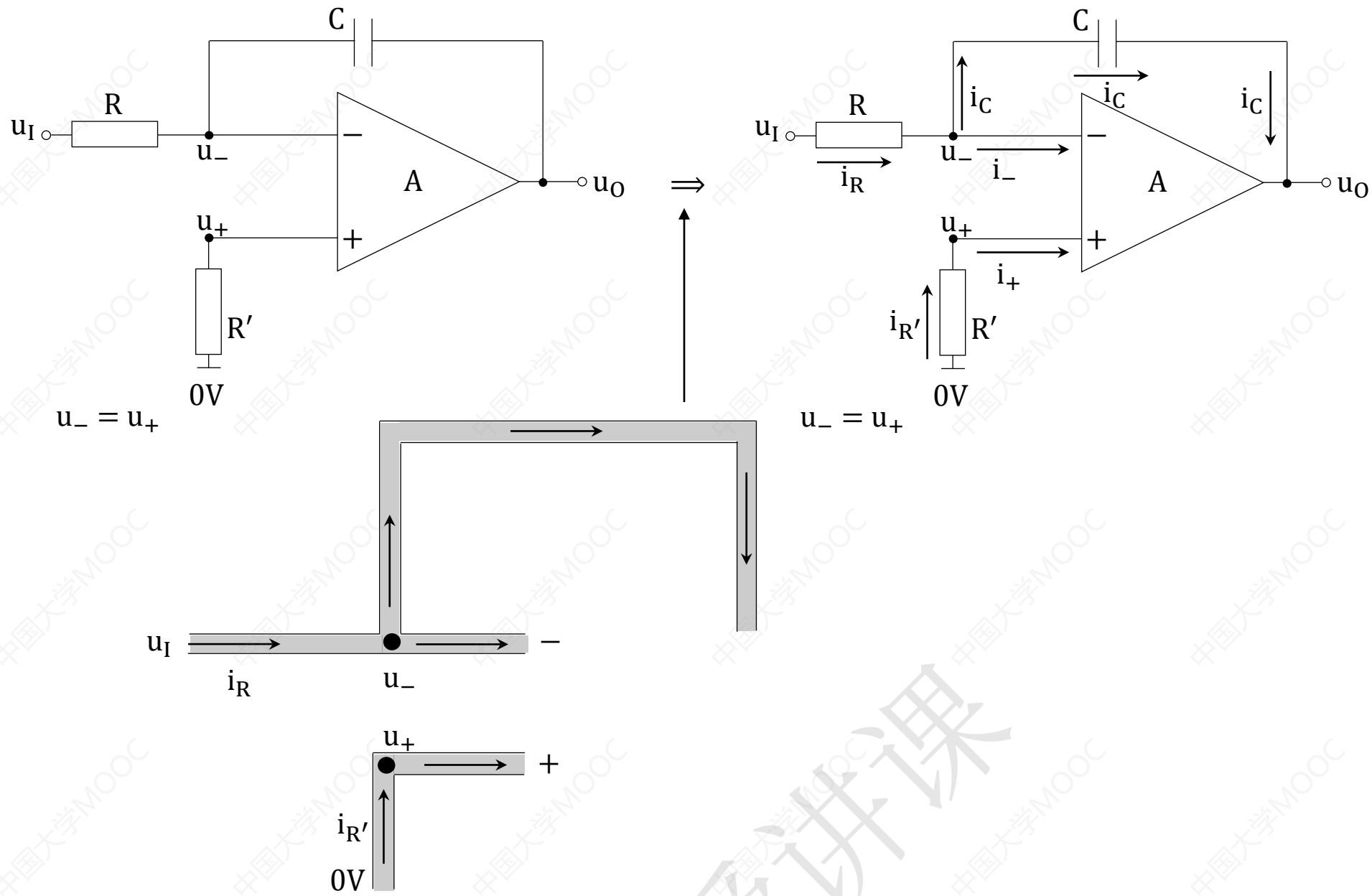
且$u_- = u_+$



③ 画出输入端以及支路的电流方向

a、假设电流从两个输入端流入

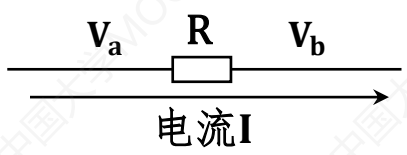
b、将电流看做水流，将导线与元件看做水管，画出水流方向即电流方向



④ 分析 u_+ 处、u_- 处电流大小关系

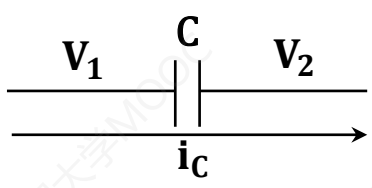
“+”号与 u_+ 之间的电流为0

“−”号与 u_- 之间的电流为0

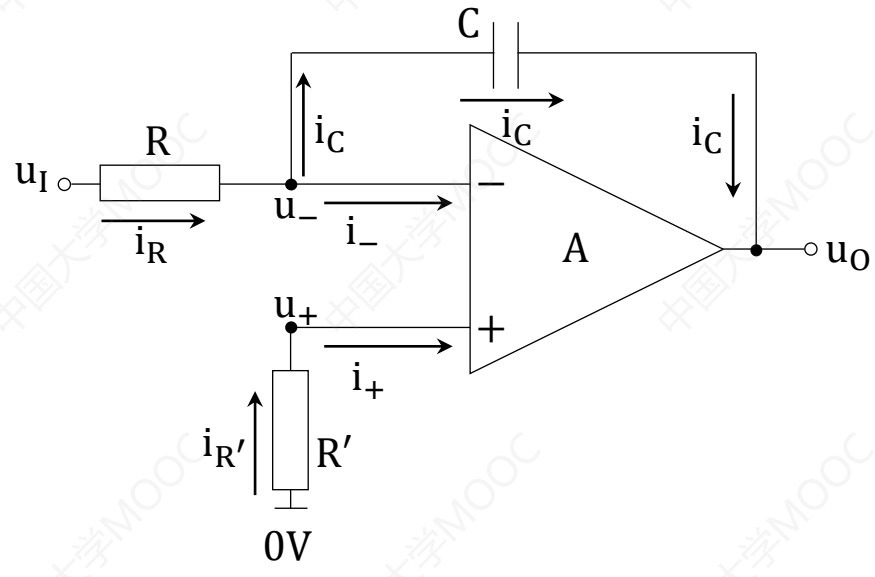


：$I = \frac{V_a - V_b}{R}$

【若无电流流经电阻，则电阻两端电位相等】



：$i_C = C \cdot \frac{d(V_1 - V_2)}{dt}$



$u_- = u_+ = 0V$

u_+：$u_+ = 0V$

u_-：$i_R = i_C$

$\Rightarrow \frac{u_I - u_-}{R} = C \cdot \frac{d(u_- - u_O)}{dt}$

$\Rightarrow \frac{u_I - 0V}{R} = C \cdot \frac{d(0V - u_O)}{dt}$

$\Rightarrow \frac{u_I}{R} = C \cdot \frac{d(-u_O)}{dt}$

$\Rightarrow \frac{u_I}{R} = -C \cdot \frac{du_O}{dt}$

$\Rightarrow du_O = -\frac{u_I}{RC} dt$

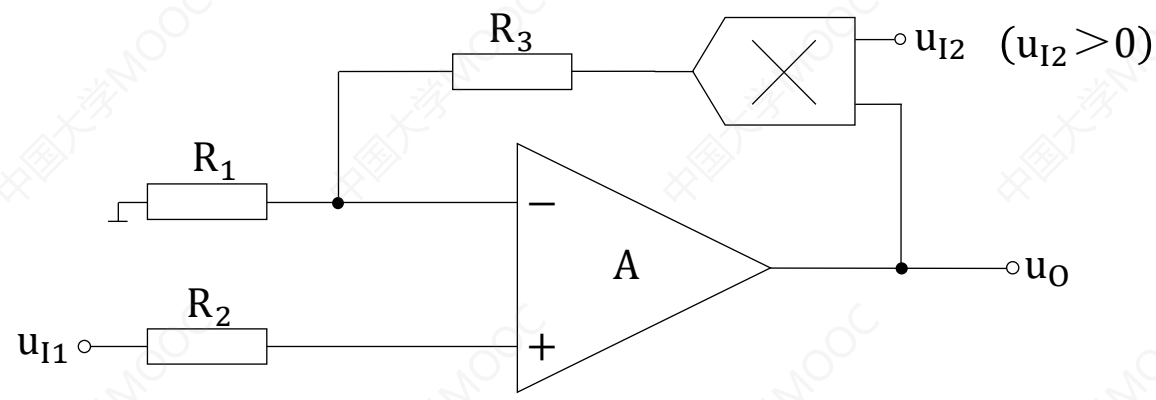
$\Rightarrow \int du_O = \int -\frac{u_I}{RC} dt$

$\Rightarrow \int 1 du_O = \int -\frac{1}{RC} u_I dt$

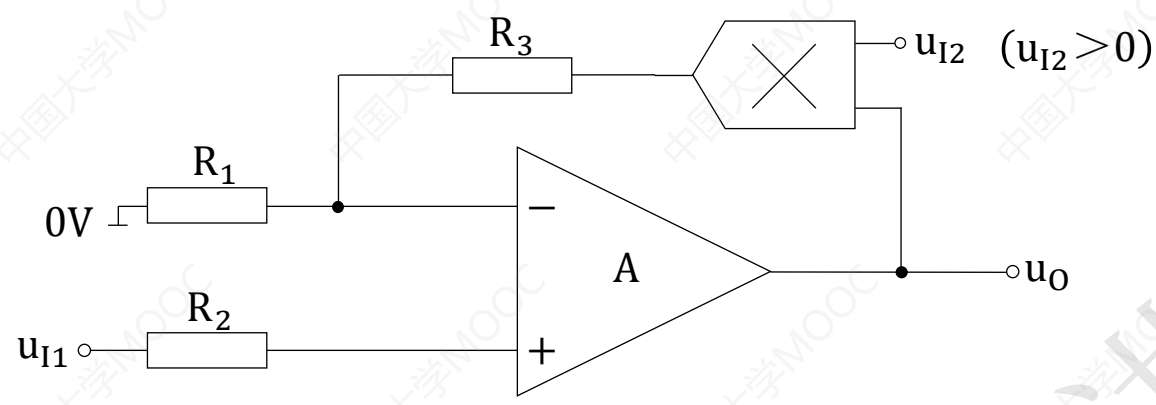
$\Rightarrow u_O = -\frac{1}{RC} \int u_I dt$

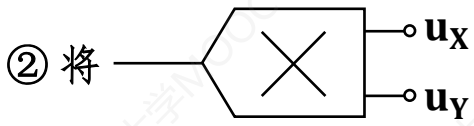
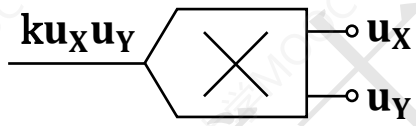
乘法模拟器

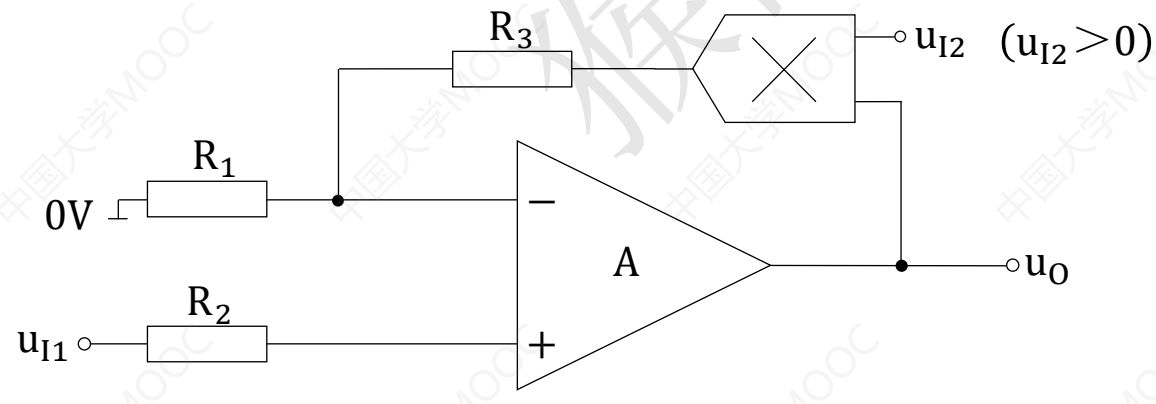
例1. 电路如图所示，已知u_{I1}、u_{I2}、R_1、R_2、R_3，
乘法模拟器的乘积系数$k=0.2$，求u_O



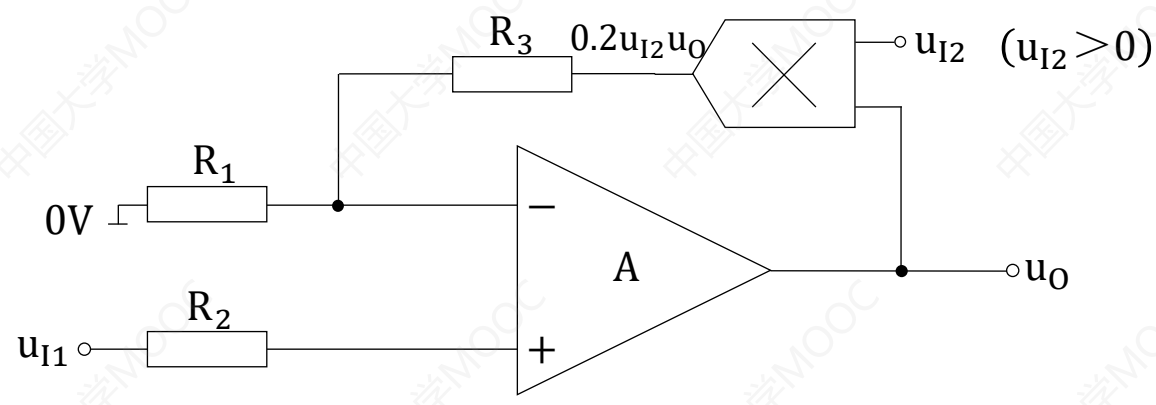
① 将各电压直接看做该点的电位，接地处电位为0V



② 将  变成 

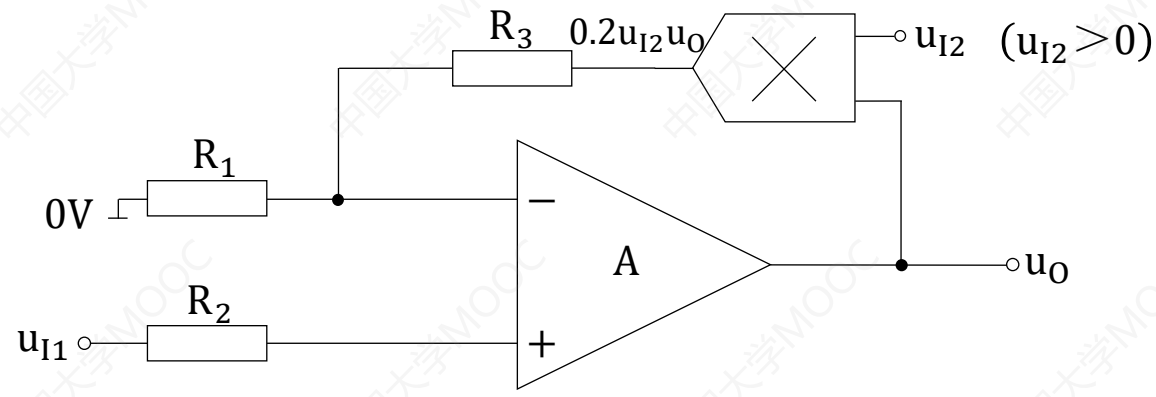


⇓

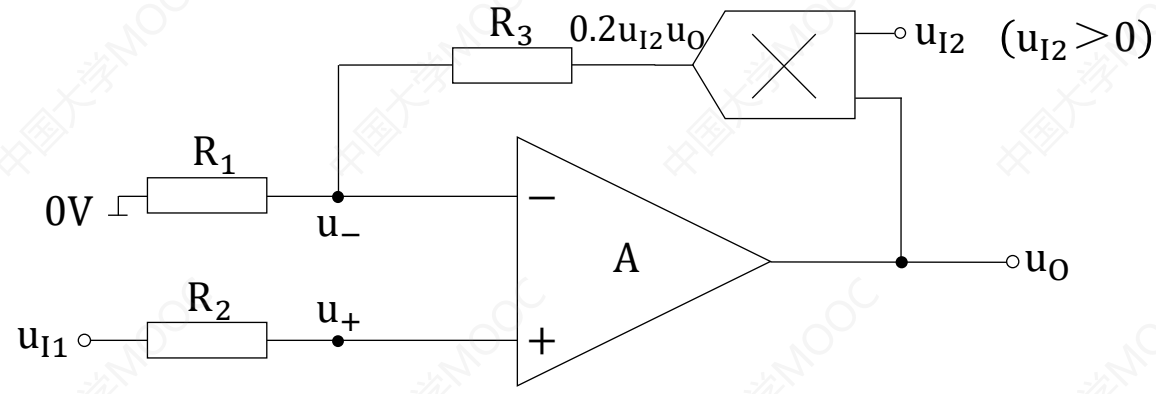


③ 在“+”号前面标上 $\mathbf{u_+}$，在“−”号前面标上 $\mathbf{u_-}$

且 $\mathbf{u_- = u_+}$



⇓

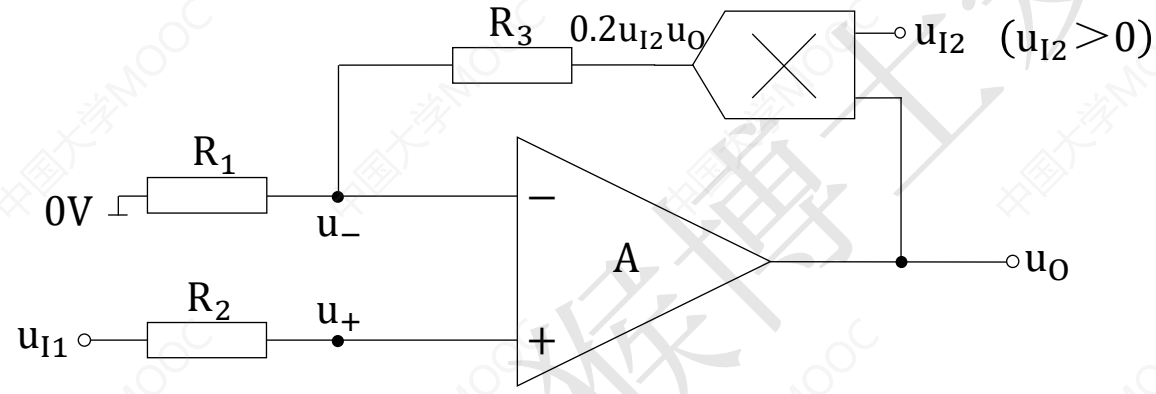


$u_- = u_+$

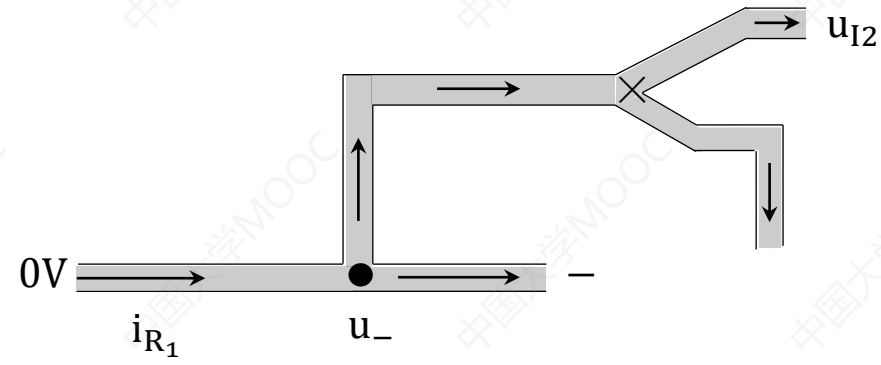
④ 画出输入端以及支路的电流方向

a、假设电流从两个输入端流入

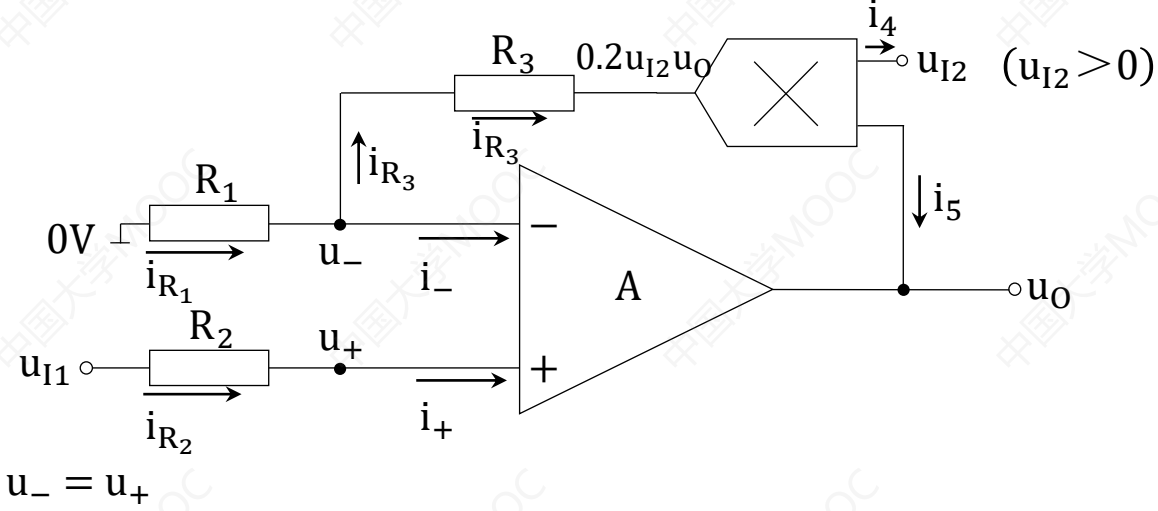
b、将电流看做水流，将导线与元件看做水管，画出水流方向即电流方向



$u_- = u_+$



⇓

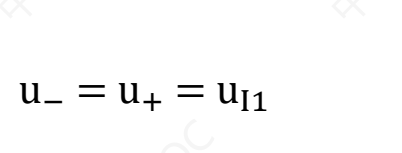


$u_- = u_+$

⑤ 分析 u_+ 处、u_- 处电流大小关系

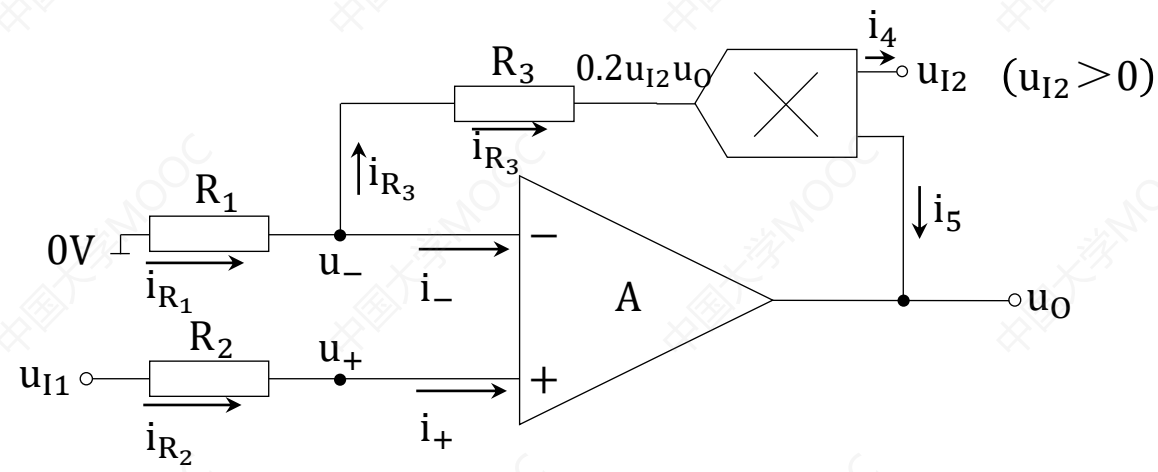
“+”号与 u_+ 之间的电流为0

“−”号与 u_- 之间的电流为0



$$：\ I=\frac{V_a-V_b}{R}$$

【若无电流流经电阻，则电阻两端电位相等】



$u_-=u_+$

$u_-=u_+=u_{I1}$

u_+处：$u_+=u_{I1}$

u_- 处：$i_{R_1}=i_{R_3}$

$$\Longrightarrow \frac{0V-u_-}{R_1}=\frac{u_--0.2u_{I2}u_O}{R_3}$$

$$\Longrightarrow \frac{0V-u_{I1}}{R_1}=\frac{u_{I1}-0.2u_{I2}u_O}{R_3}$$

$$\Longrightarrow -\frac{u_{I1}}{R_1}=\frac{u_{I1}-0.2u_Ou_{I2}}{R_3}$$

$$\Longrightarrow -R_3u_{I1}=R_1u_{I1}-0.2R_1u_Ou_{I2}$$

$$\Longrightarrow 0.2R_1u_Ou_{I2}=R_1u_{I1}+R_3u_{I1}$$

$$\Longrightarrow 0.2R_1u_Ou_{I2}=(R_1+R_3)u_{I1}$$

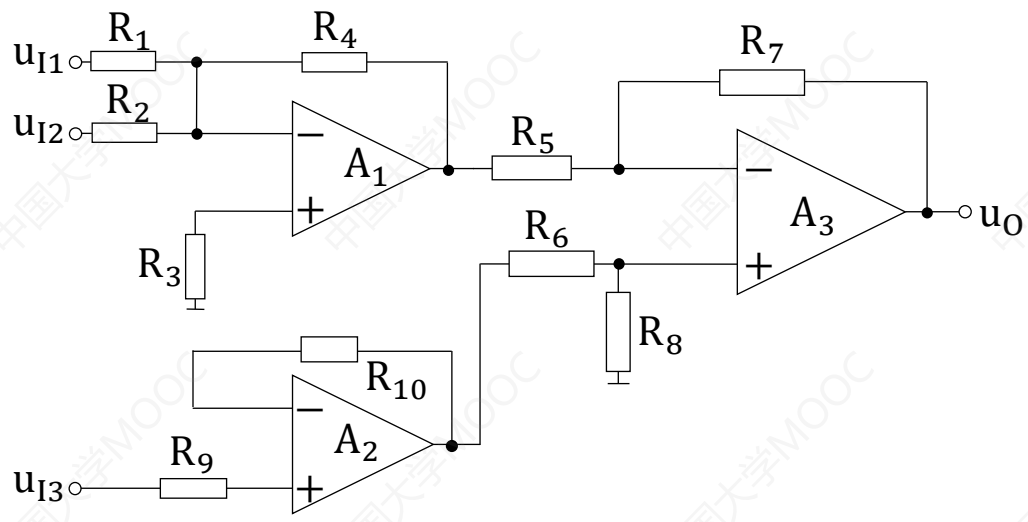
$$\Longrightarrow R_1u_Ou_{I2}=5(R_1+R_3)u_{I1}$$

$$\Longrightarrow u_O=\frac{5(R_1+R_3)u_{I1}}{R_1u_{I2}}$$

组合运算电路

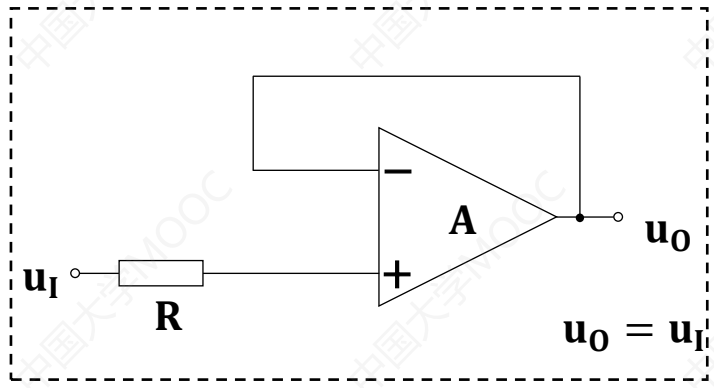
例1. 电路如图所示，其中，$R_1=1k\Omega$，$R_2=1k\Omega$，$R_3=3k\Omega$，$R_4=1k\Omega$

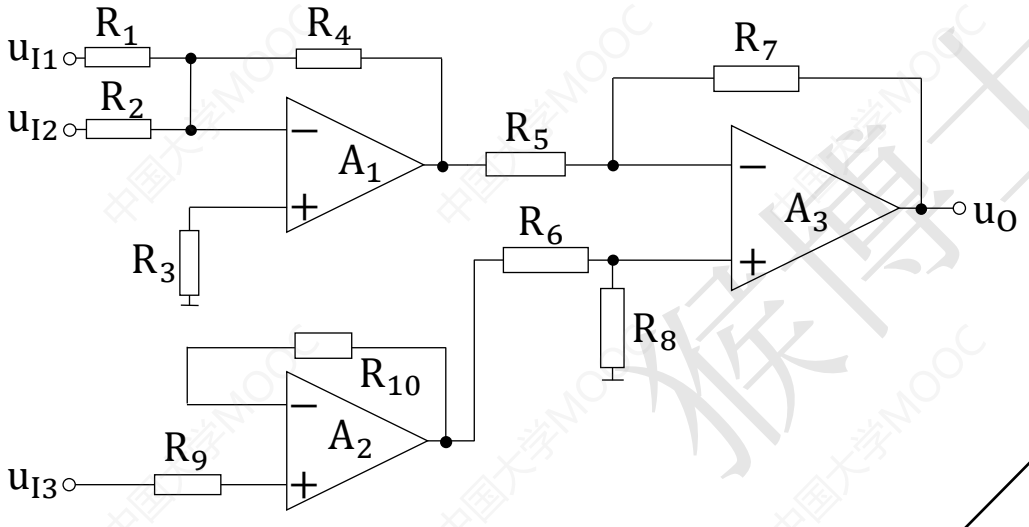
$R_5=2k\Omega$，$R_6=2k\Omega$，$R_7=4k\Omega$，$R_8=4k\Omega$，求输出电压u_O的表达式



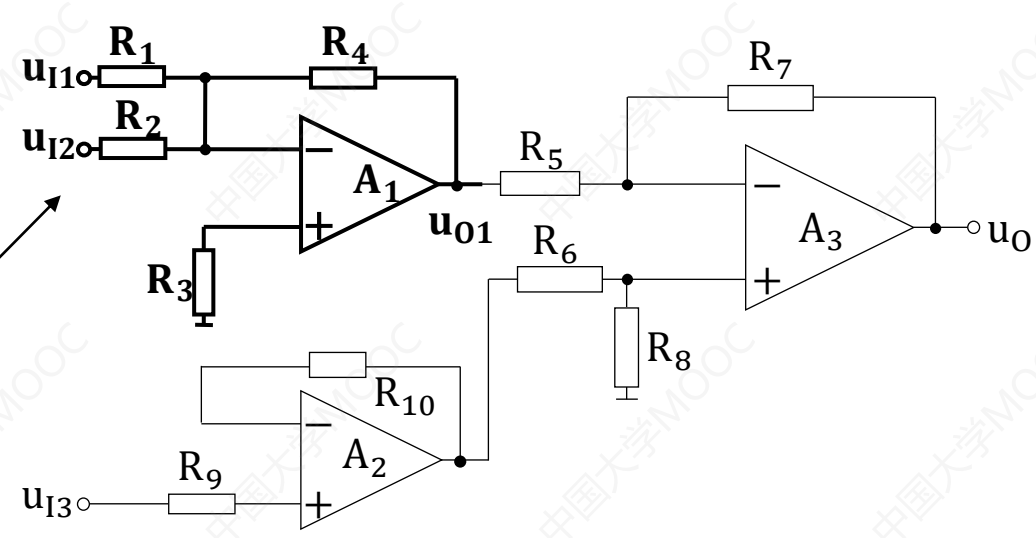
① 算一下最左边集成运放的输出电压

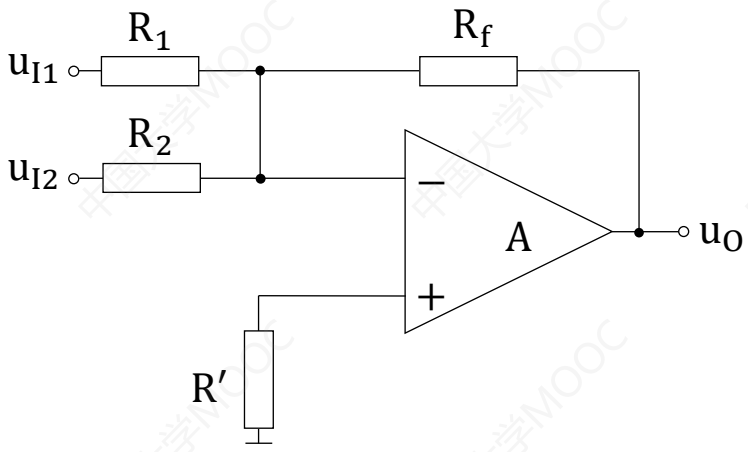
【电压跟随器】





⇒





$$u_O=-\frac{R_f}{R_1}\cdot u_{I1}-\frac{R_f}{R_2}\cdot u_{I2}$$

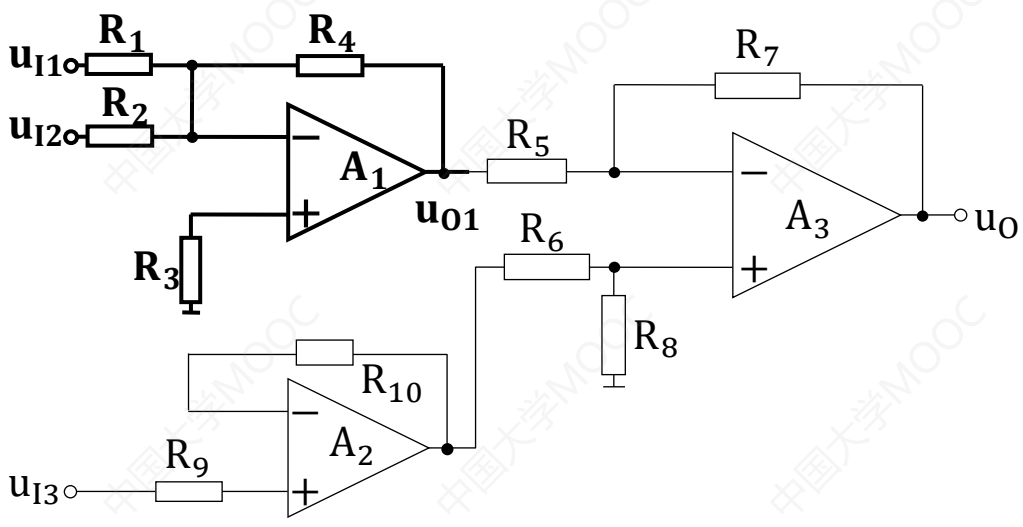
$$u_{O1}=-\frac{R_4}{R_1}\cdot u_{I1}-\frac{R_4}{R_2}\cdot u_{I2}$$

$$=-\frac{1k\Omega}{1k\Omega}\cdot u_{I1}-\frac{1k\Omega}{1k\Omega}\cdot u_{I2}$$

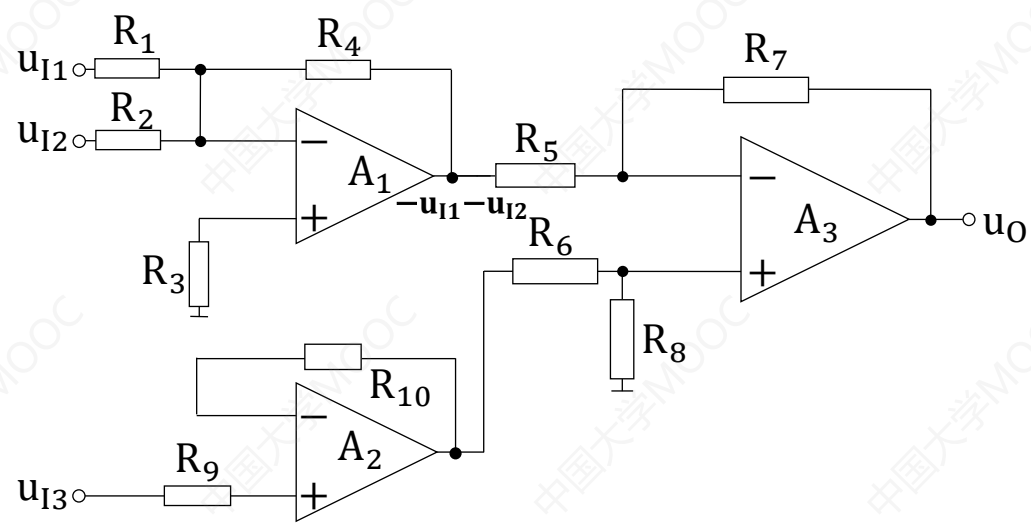
$$=-u_{I1}-u_{I2}$$

详见【集成运放应用】第3课【反相加法运算电路】

② 只保留该输出电压，重复进行步骤①



$\Rightarrow$



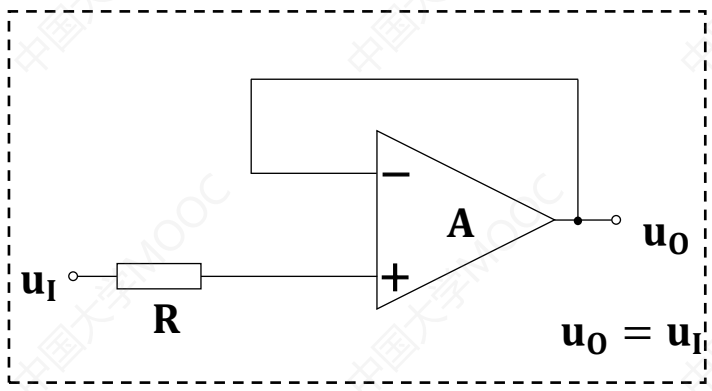
$$u_{O1} = -\frac{R_4}{R_1}\cdot u_{I1} - \frac{R_4}{R_2}\cdot u_{I2}$$

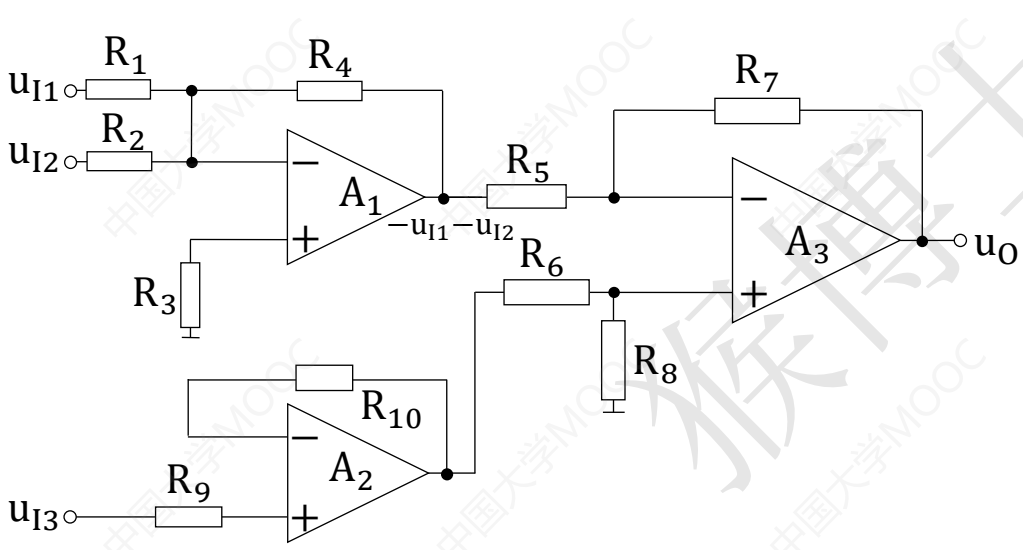
$$= -\frac{1k\Omega}{1k\Omega}\cdot u_{I1} - \frac{1k\Omega}{1k\Omega}\cdot u_{I2}$$

$$= -u_{I1} - u_{I2}$$

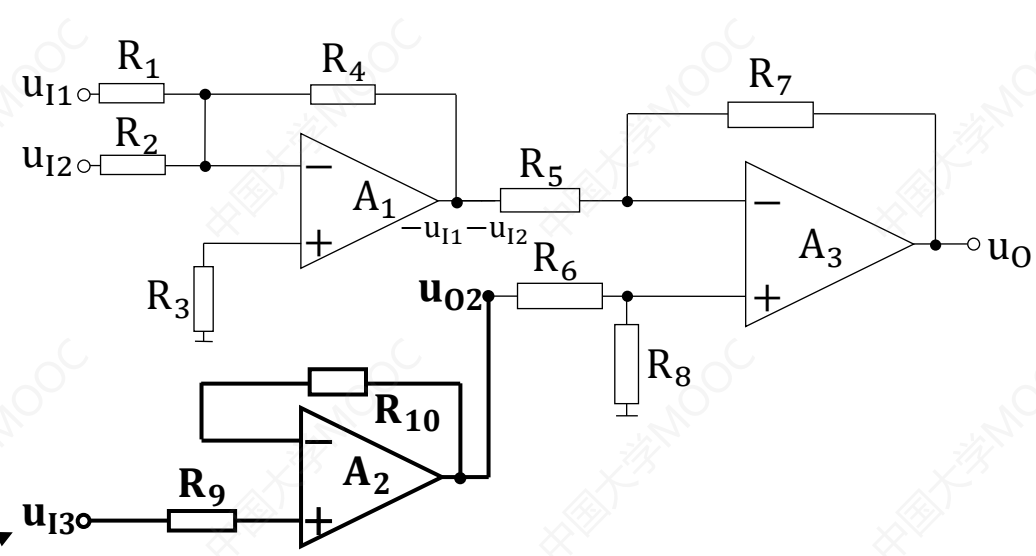
① 算一下最左边集成运放的输出电压

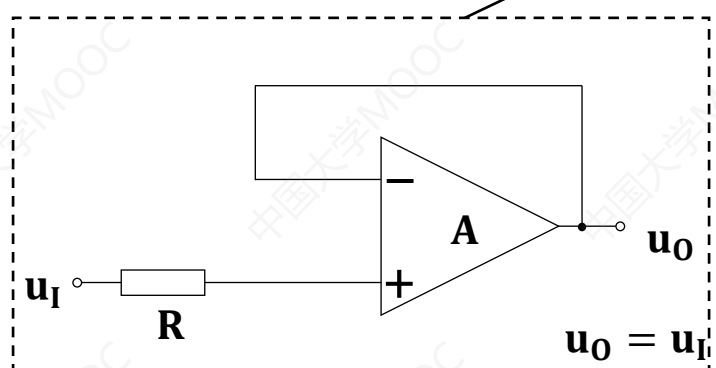
【电压跟随器】





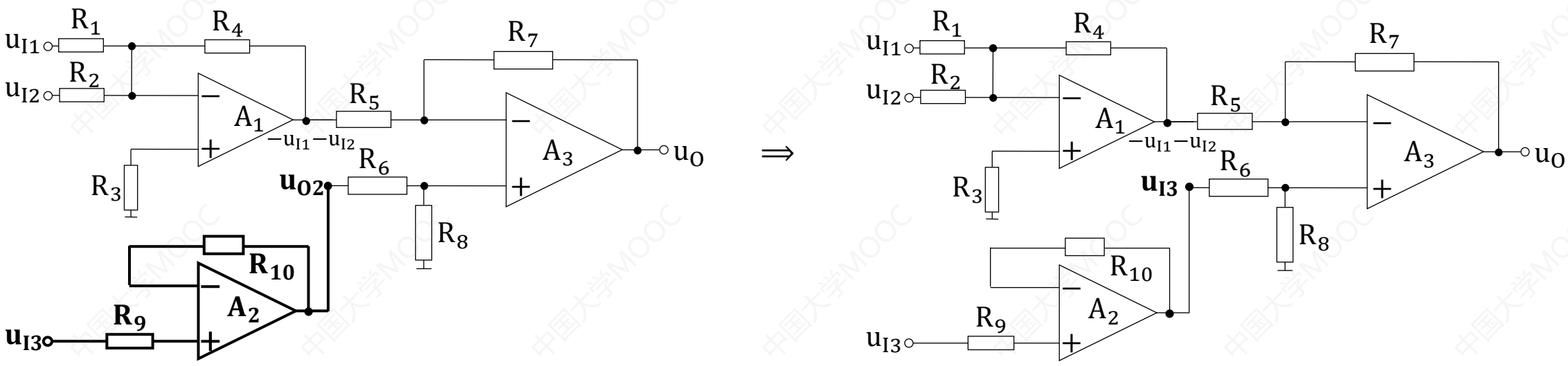
$\Rightarrow$





$u_{O2} = u_{I3}$

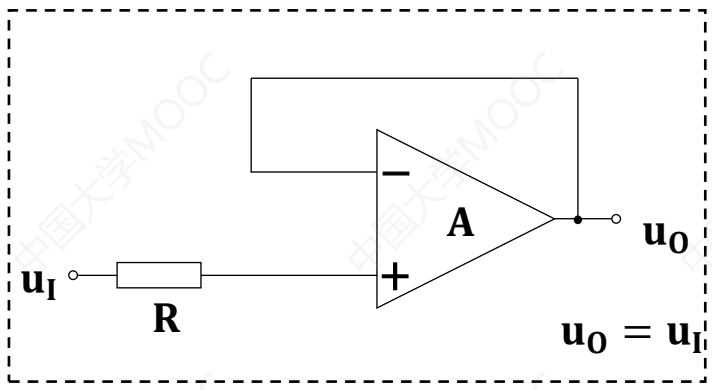
② 只保留该输出电压，重复进行步骤①

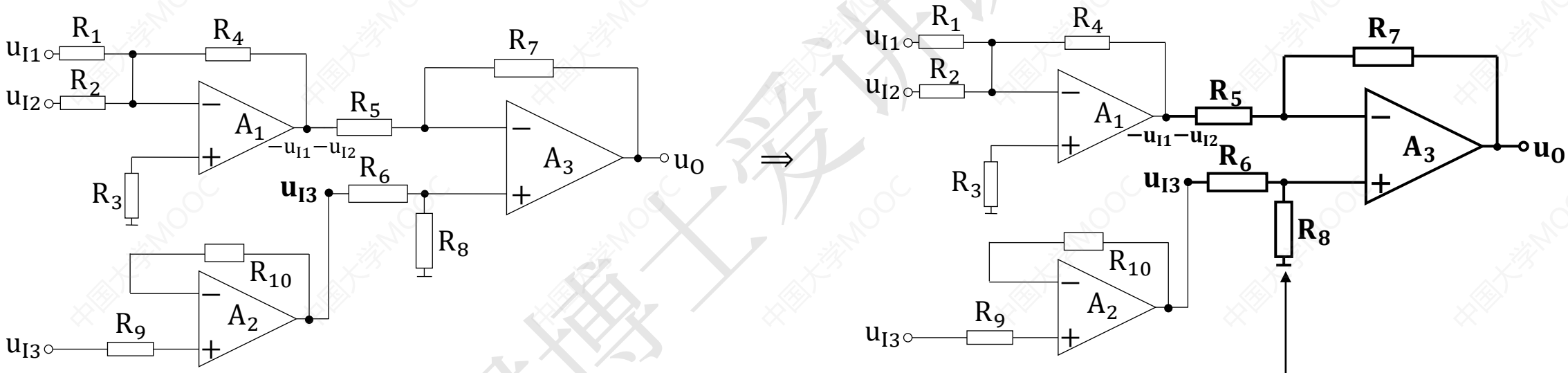


$\mathbf{u_{O2} = u_{I3}}$

① 算一下最左边集成运放的输出电压

【电压跟随器】

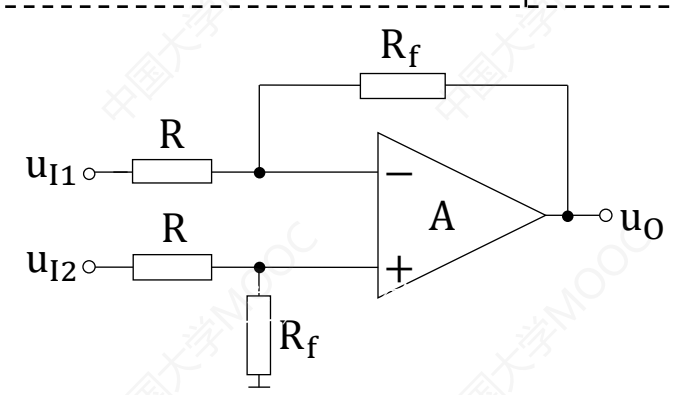




$$u_O = \frac{R_7}{R_5}\cdot[u_{I3} - (-u_{I1}-u_{I2})]$$

$$= \frac{4k\Omega}{2k\Omega}\cdot[u_{I3} - (-u_{I1}-u_{I2})]$$

$$= 2(u_{I1}+u_{I2}+u_{I3})$$



$$u_O = \frac{R_f}{R}\cdot(u_{I2} - u_{I1})$$

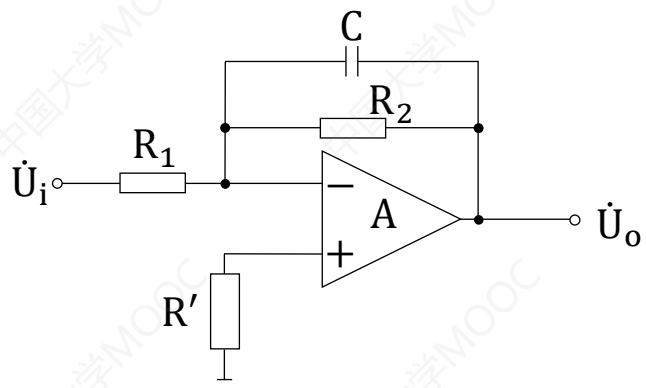
详见【集成运放应用】第5课【减法运算电路】

有源滤波电路

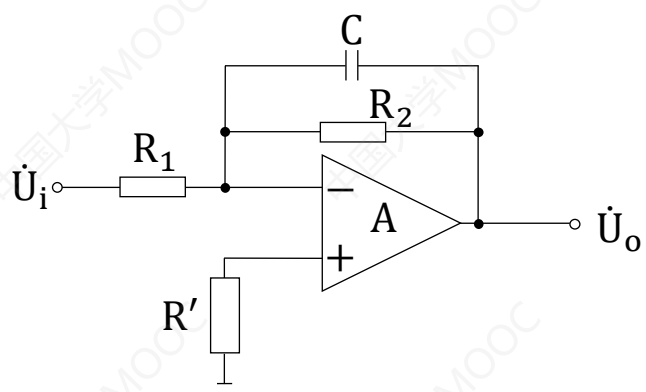
例1. 电路如图所示，已知 $\mathrm{R_1}=\mathrm{R_2}$ ，$\dot{\mathrm{U}}_\mathrm{i}\neq 0$

(1) 判断该电路是高通滤波电路还是低通滤波电路，写出分析过程

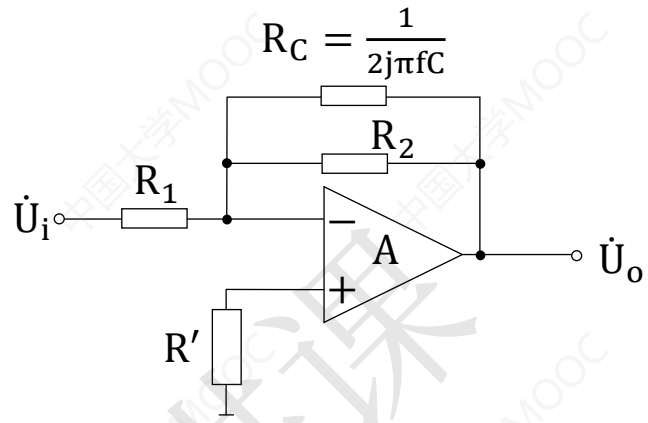
(2) 求通带放大倍数$\dot{\mathrm{A}}_{\mathrm{up}}$

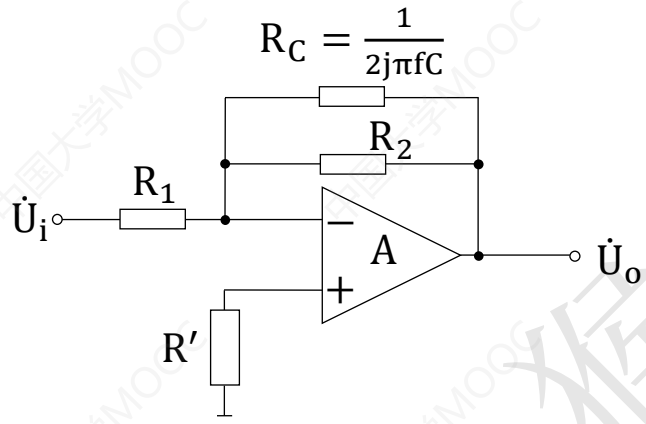


① 将 “ $\mathbf{C}$ ” 变成 “ $\mathbf{R_C=\frac{1}{2j\pi fC}}$ ”

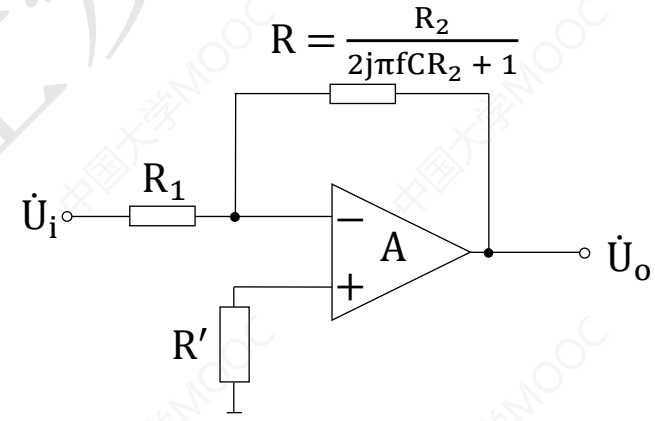


$\Longrightarrow$



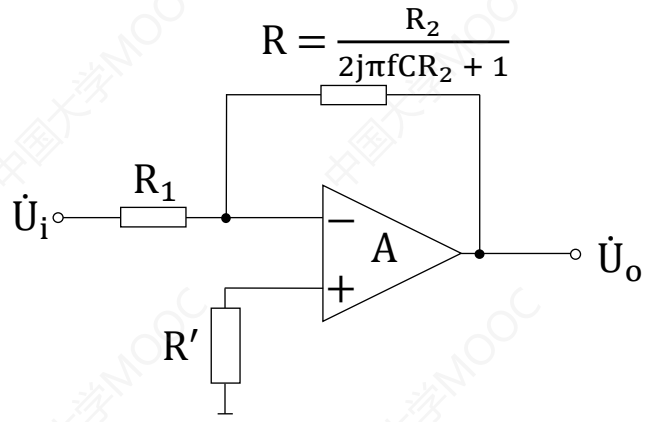


$\Longrightarrow$



$$\mathrm{R}=\mathrm{R_2}//\mathrm{R_C}=\frac{\mathrm{R_2}\cdot\mathrm{R_C}}{\mathrm{R_2}+\mathrm{R_C}}=\frac{\mathrm{R_2}\cdot\frac{1}{2j\pi fC}}{\mathrm{R_2}+\frac{1}{2j\pi fC}}=\frac{\mathrm{R_2}}{2j\pi fCR_2+1}$$

③ 求出 $\dot{\mathbf{U}}_\mathbf{o}$

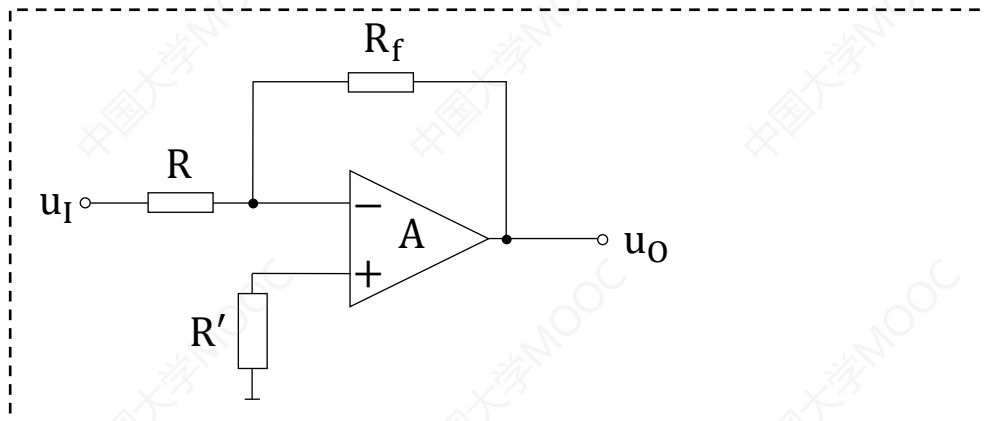


$$\dot{\mathrm{U}}_\mathrm{o}=-\frac{\frac{\mathrm{R_2}}{2j\pi fCR_2+1}}{\mathrm{R_1}}\dot{\mathrm{U}}_\mathrm{i}$$

$$=-\frac{\mathrm{R_2}}{\mathrm{R_1}(2j\pi fCR_2+1)}\dot{\mathrm{U}}_\mathrm{i}$$

$$=-\frac{\mathrm{R_2}}{\mathrm{R_2}(2j\pi fCR_2+1)}\dot{\mathrm{U}}_\mathrm{i}$$

$$=-\frac{1}{2j\pi fCR_2+1}\dot{\mathrm{U}}_\mathrm{i}$$



$$u_O=-\frac{R_f}{R}\cdot u_I$$

详见【集成运放应用】第1课【反相比例运算电路】

④ 判断该电路类型，求通带放大倍数$\dot{A}_{up}$

a、令 $f=0$，求得 $\dot{U}_o$ 的值 $\dot{U}_{o零}$

令 $f=\infty$，求得 $\dot{U}_o$ 的值 $\dot{U}_{o\infty}$

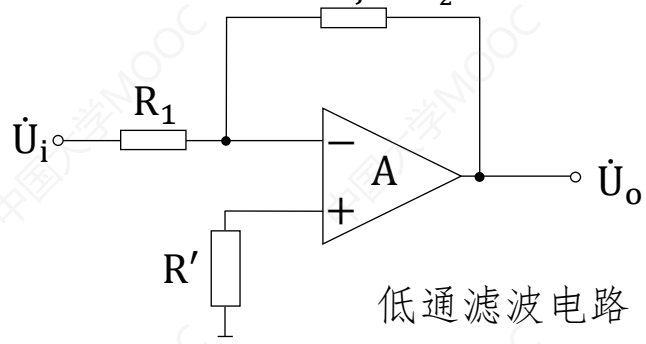
b、若 $\dot{U}_{o零}\neq 0$，$\dot{U}_{o\infty}=0$，为低通滤波电路

$$\dot{A}_{up}=\frac{\dot{U}_{o零}}{\dot{U}_i}$$

若 $\dot{U}_{o零}=0$，$\dot{U}_{o\infty}\neq 0$，为高通滤波电路

$$\dot{A}_{up}=\frac{\dot{U}_{o\infty}}{\dot{U}_i}$$

$$R=\frac{R_2}{2j\pi fCR_2+1}$$



低通滤波电路

$$\dot{U}_o=-\frac{\frac{R_2}{2j\pi fCR_2+1}}{R_1}\dot{U}_i$$

$$=-\frac{R_2}{R_1(2j\pi fCR_2+1)}\dot{U}_i$$

$$=-\frac{R_2}{R_2(2j\pi fCR_2+1)}\dot{U}_i$$

$$=-\frac{1}{2j\pi fCR_2+1}\dot{U}_i$$

$$\dot{U}_{o零}=-\frac{1}{2j\pi\cdot 0\cdot CR_2+1}\dot{U}_i=-\frac{1}{0+1}\dot{U}_i=-\dot{U}_i\neq 0$$

$$\dot{U}_{o\infty}=-\frac{1}{2j\pi\cdot\infty\cdot CR_2+1}\dot{U}_i$$

$$=-\frac{1}{\infty+1}\dot{U}_i$$

$$=-\frac{1}{\infty}\dot{U}_i$$

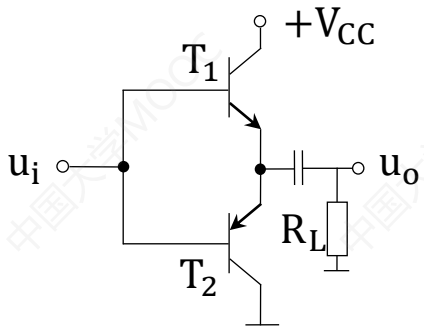
$$=-0\cdot\dot{U}_i$$

$$=0$$

$$\dot{A}_{up}=\frac{\dot{U}_{o零}}{\dot{U}_i}=\frac{-\dot{U}_i}{\dot{U}_i}=-1$$

功率放大电路

例1. 电路如图所示，$V_{CC}=12V$，$R_L=8\Omega$，输入信号 u_i 为正弦波，U_{CES} 忽略不计，求电路的最大输出功率、直流电源的功率和效率、总管耗



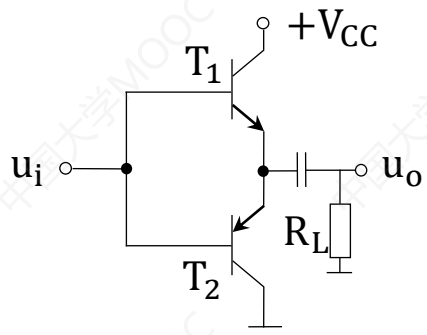
OTL放大电路：

最大不失真输出电压有效值 $\mathbf{U_{om}=\frac{\frac{V_{CC}}{2}-|U_{CES}|}{\sqrt{2}}}$

最大输出功率 $\mathbf{P_{om}=\frac{U_{om}^2}{R_L}}$

电源消耗的平均功率 $\mathbf{P_V=\frac{2}{\pi}\cdot\frac{\frac{V_{CC}}{2}\left(\frac{V_{CC}}{2}-|U_{CES}|\right)}{R_L}}$

效率 $\boldsymbol{\eta=\frac{P_{om}}{P_V}}$**、电路总管耗** $\mathbf{P_{Tm}=P_V-P_{om}}$



OTL 放大电路

$$P_{om}=\frac{U_{om}^2}{R_L}=\frac{\left(\frac{\frac{V_{CC}}{2}-|U_{CES}|}{\sqrt{2}}\right)^2}{R_L}=\frac{\left(\frac{\frac{12V}{2}-|0V|}{\sqrt{2}}\right)^2}{8\Omega}=\frac{\left(\frac{6}{\sqrt{2}}\right)^2}{8\Omega}W=2.25W$$

$$P_V=\frac{2}{\pi}\cdot\frac{\frac{V_{CC}}{2}\left(\frac{V_{CC}}{2}-|U_{CES}|\right)}{R_L}=\frac{2}{\pi}\cdot\frac{\frac{12V}{2}\left(\frac{12V}{2}-|0V|\right)}{8\Omega}=\frac{2}{3.14}\cdot\frac{6V\times6V}{8\Omega}=2.87W$$

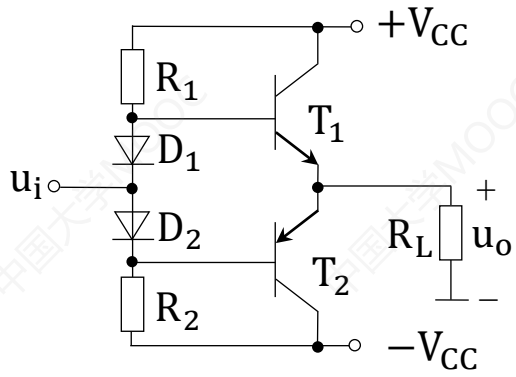
$$\eta=\frac{P_{om}}{P_V}=\frac{2.25W}{2.87W}=78.5\%$$

$$P_{Tm}=P_V-P_{om}=2.87W-2.25W=0.62W$$

例2. 电路如图所示，$V_{CC}=19V$，$R_L=16\Omega$，输入信号 u_i 为正弦波 $|U_{CES}|=1V$，求：

(1) 电路的U_{om}、P_{om}、P_V、η

(2) 求三极管的极限参数



OCL放大电路：

最大不失真输出电压有效值$U_{om}=\frac{V_{CC}-|U_{CES}|}{\sqrt{2}}$

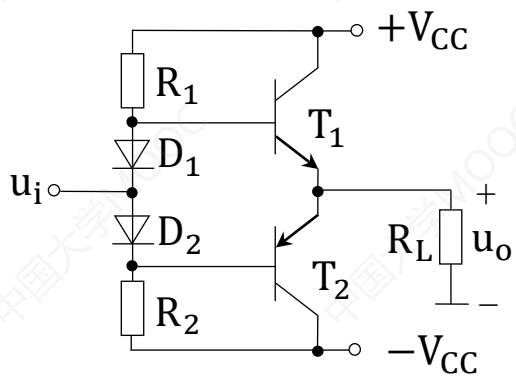
最大输出功率 $P_{om}=\frac{U_{om}^2}{R_L}$

电源消耗的平均功率 $P_V=\frac{2}{\pi}\cdot\frac{V_{CC}(V_{CC}-|U_{CES}|)}{R_L}$

效率 $\eta=\frac{P_{om}}{P_V}$、电路总管耗 $P_{Tm}=P_V-P_{om}$

三极管极限参数

- 集电极极限电流$I_{CM}\geq\frac{V_{CC}}{R_L}$
- 最大允许反向电压 $|U_{(BR)CEO}|>2V_{CC}$
- 单个三极管最大允许管耗：$P_{CM}\geq\frac{V_{CC}^2}{\pi^2R_L}$



OCL 放大电路

(1) $U_{om}=\frac{V_{CC}-|U_{CES}|}{\sqrt{2}}=\frac{19V-1V}{\sqrt{2}}=12.73V$

$P_{om}=\frac{U_{om}^2}{R_L}=\frac{(12.73V)^2}{16\Omega}=10.13W$

$P_V=\frac{2}{\pi}\cdot\frac{V_{CC}(V_{CC}-|U_{CES}|)}{R_L}=\frac{2}{\pi}\cdot\frac{19V(19V-1V)}{16\Omega}=13.61W$

$\eta=\frac{P_{om}}{P_V}=\frac{10.13W}{13.61W}=74.4\%$

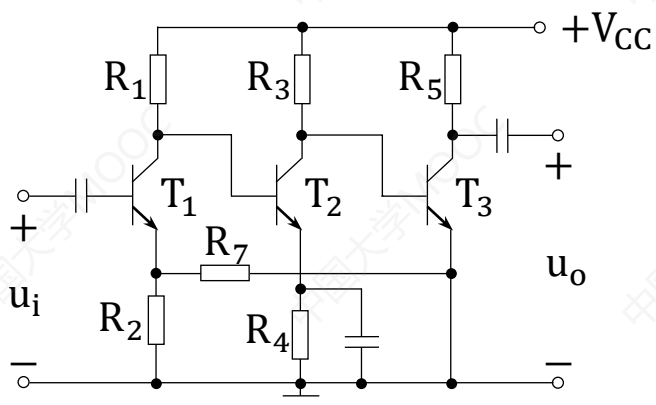
(2) $I_{CM}\geq\frac{V_{CC}}{R_L}\Longrightarrow I_{CM}\geq\frac{19V}{16\Omega}\Longrightarrow I_{CM}\geq 1.1875A$

$|U_{(BR)CEO}|>2V_{CC}\Longrightarrow|U_{(BR)CEO}|>2\times19V\Longrightarrow|U_{(BR)CEO}|>38V$

$P_{CM}\geq\frac{V_{CC}^2}{\pi^2R_L}\Longrightarrow P_{CM}\geq\frac{(19V)^2}{3.14^2\times16\Omega}\Longrightarrow P_{CM}\geq 2.28W$

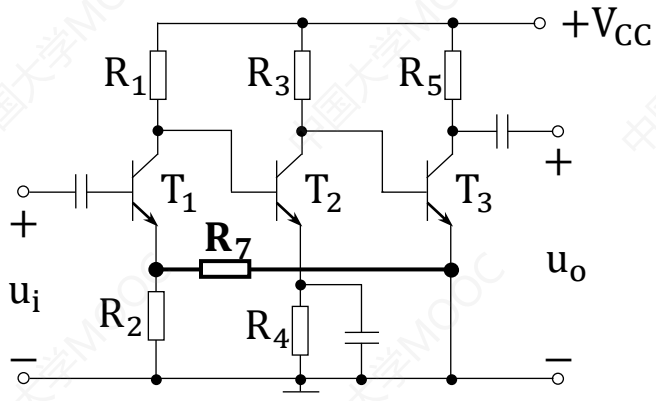
反馈组态的判断

例1. 电路如图所示，请判断电路的交流反馈组态

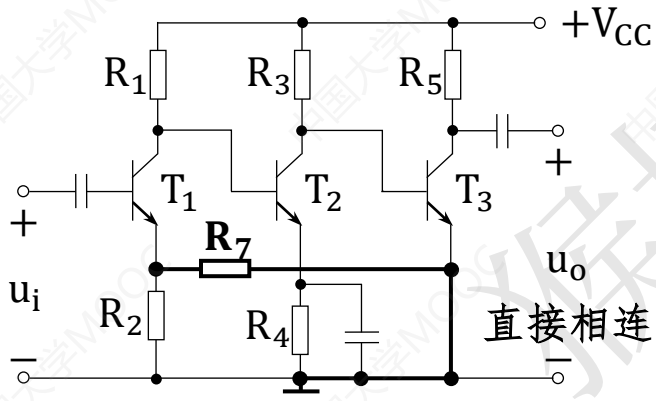


① 找反馈通路

a、找到只横跨最左边放大元件和最右边放大元件的路径



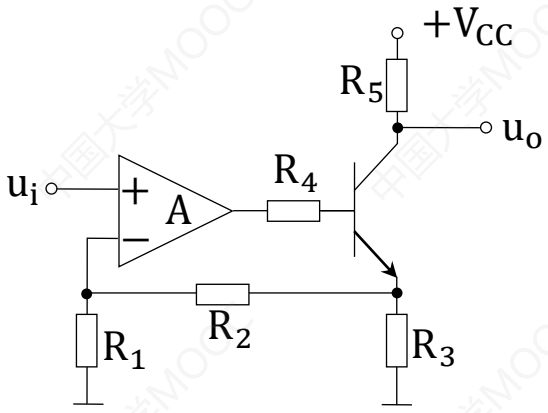
b、观察该路径是否与地直接相连



不存在反馈通路

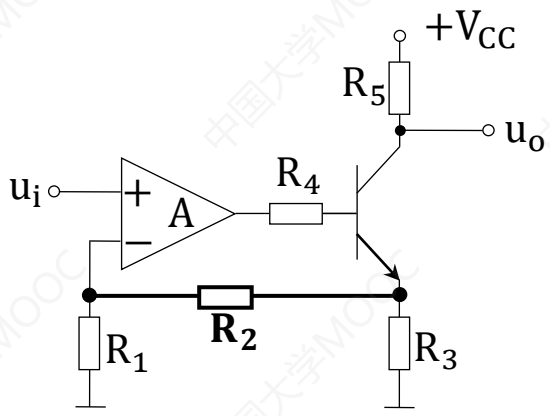
$\Longrightarrow$ 不存在反馈

例2. 电路如图所示，请判断电路的交流反馈组态

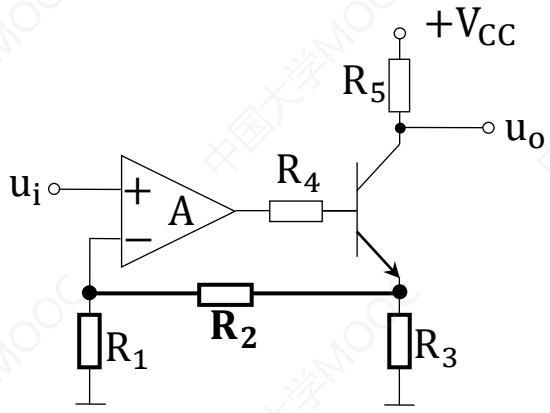


① 找反馈通路

a、找到只横跨最左边放大元件和最右边放大元件的路径

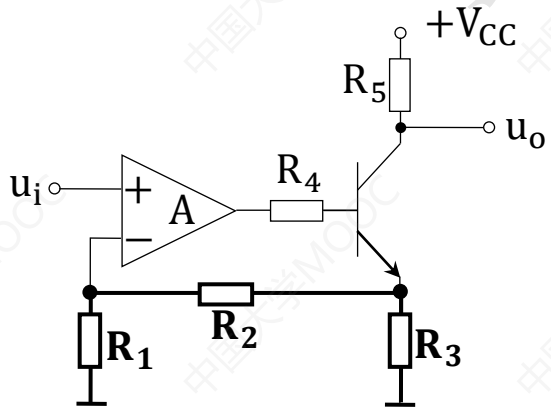


b、观察该路径是否与地直接相连



c、该路径+与他相连的地+他和地之间的部分为反馈通路

【注意：这里要找的反馈通路不能包含只横跨一个放大元件的部分】

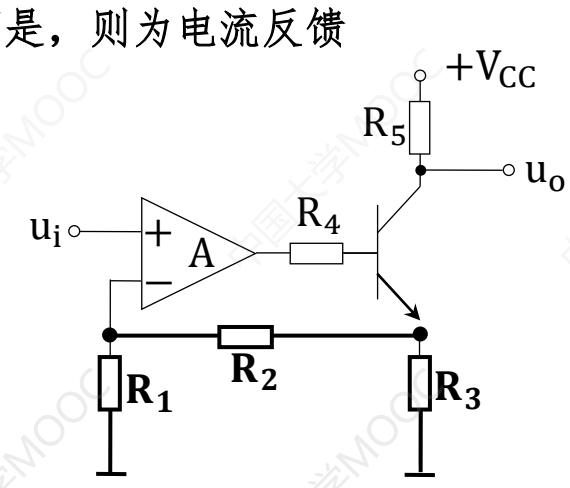


② 判断反馈为电压反馈还是电流反馈

观察反馈通路与 $\mathbf{u_o}$ 或 $\mathbf{u_o}$的“＋”之间是否只有导线

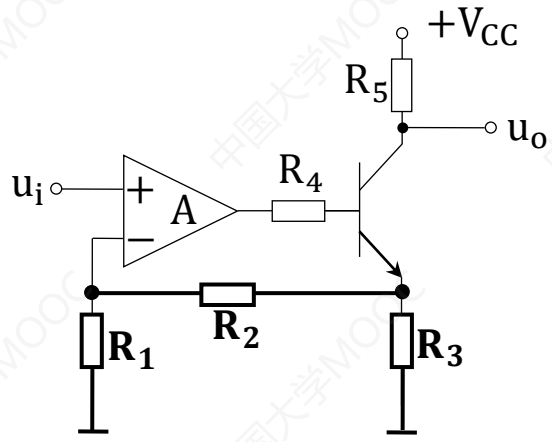
若是，则为电压反馈

若不是，则为电流反馈



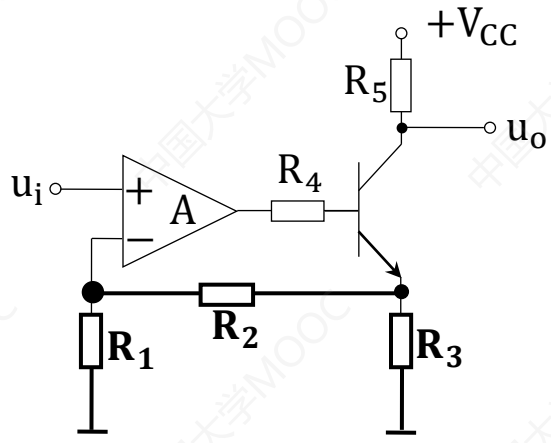
电流反馈

③ 判断反馈为串联反馈还是并联反馈



电流反馈

a、找到反馈通路与最左边放大元件输入端的交点

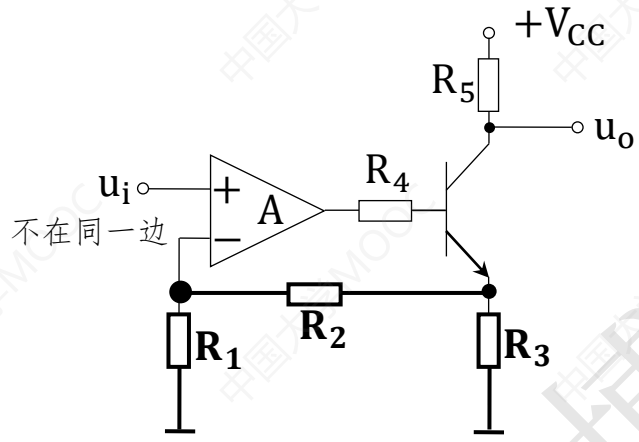


电流反馈

b、观察该交点与输入信号 u_i 是否在同一边

若该交点与输入信号 u_i 在同一边，则为并联反馈

若该交点与输入信号 u_i 不在同一边，则为串联反馈

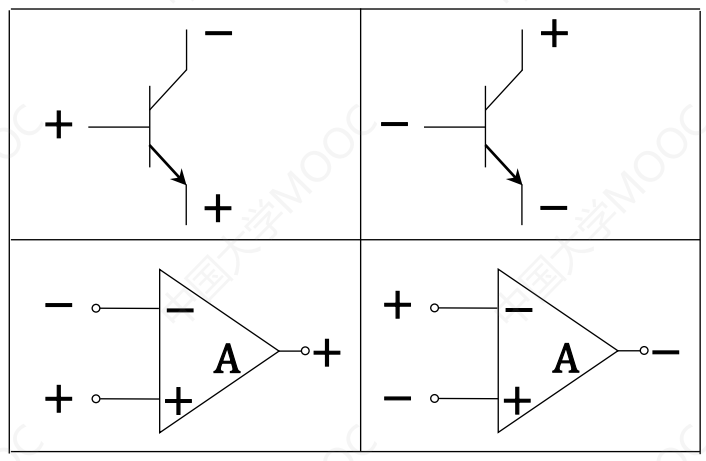


串联反馈

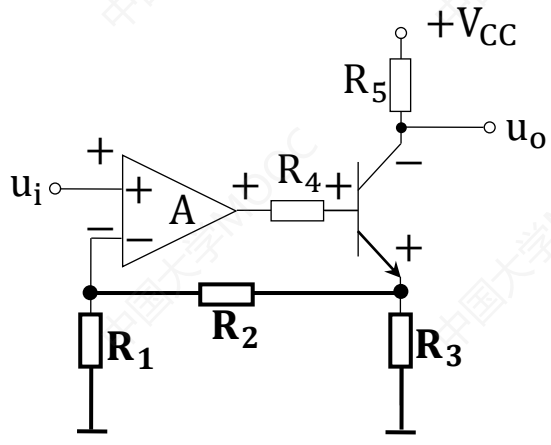
④ 判断反馈为正反馈还是负反馈

a、假设 u_i 为正，判断所有三极管和集成运放各端极性

常见的极性关系图：



【电阻、导线、电容不影响极性】

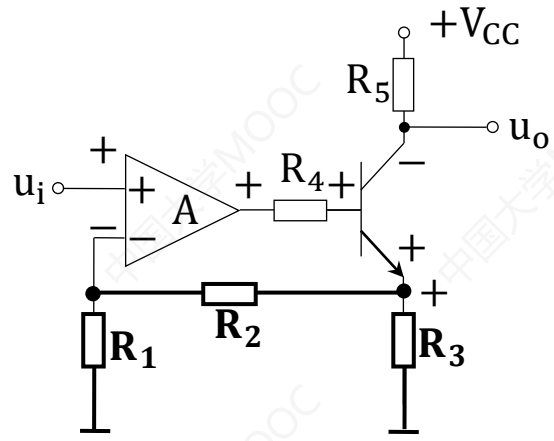


电流反馈

串联反馈

b、标出反馈通路右端的极性，判断正负反馈

并联反馈	串联反馈
极性正，正反馈 极性负，负反馈	极性正，负反馈 极性负，正反馈



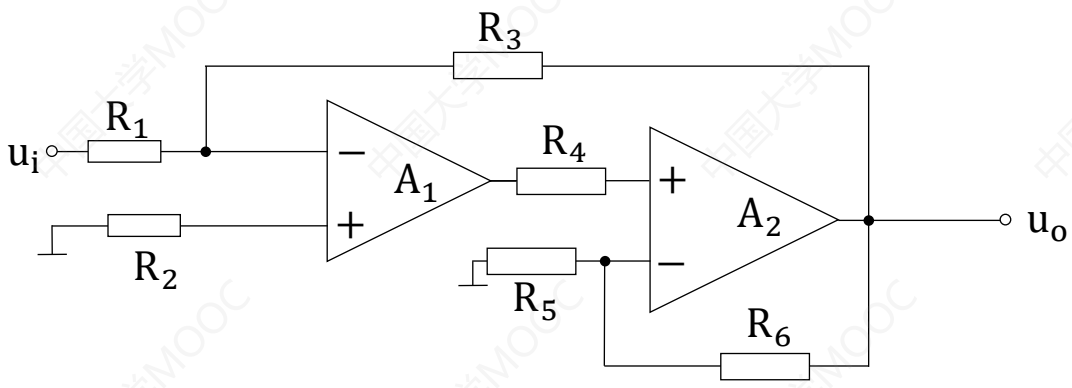
电流反馈

串联反馈

负反馈

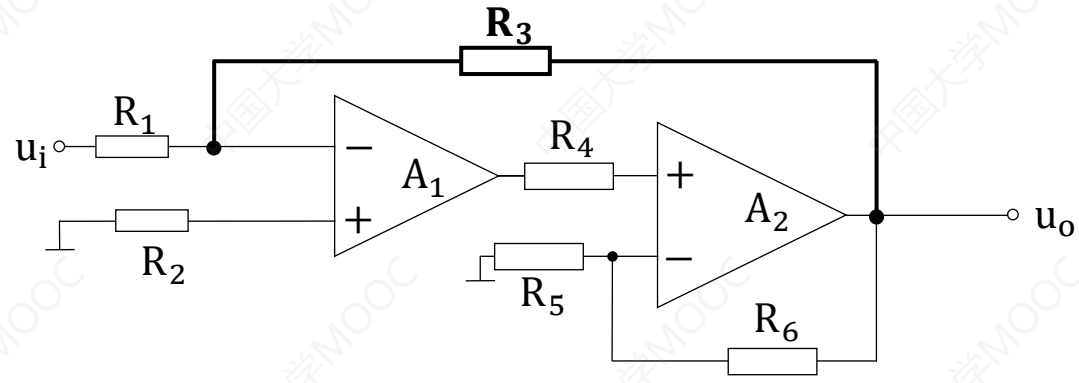
⟹ 电流串联负反馈

例3. 电路如图所示，请判断电路的交流反馈组态

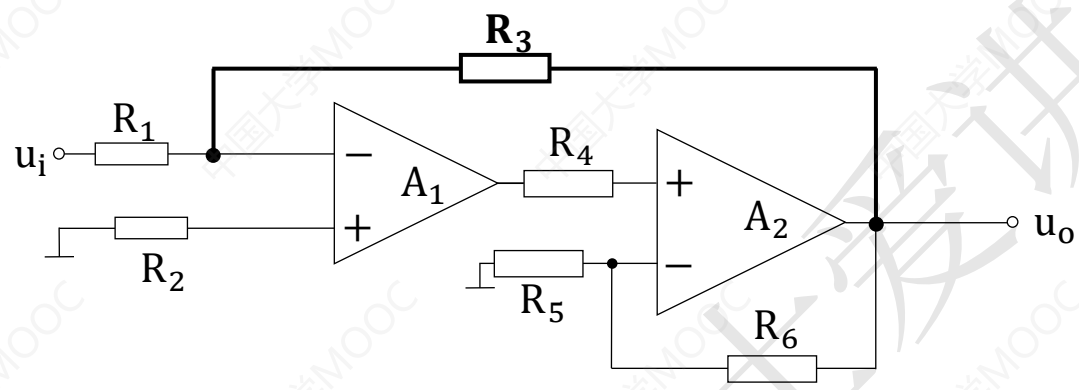


① 找反馈通路

a、找到只横跨最左边放大元件和最右边放大元件的路径

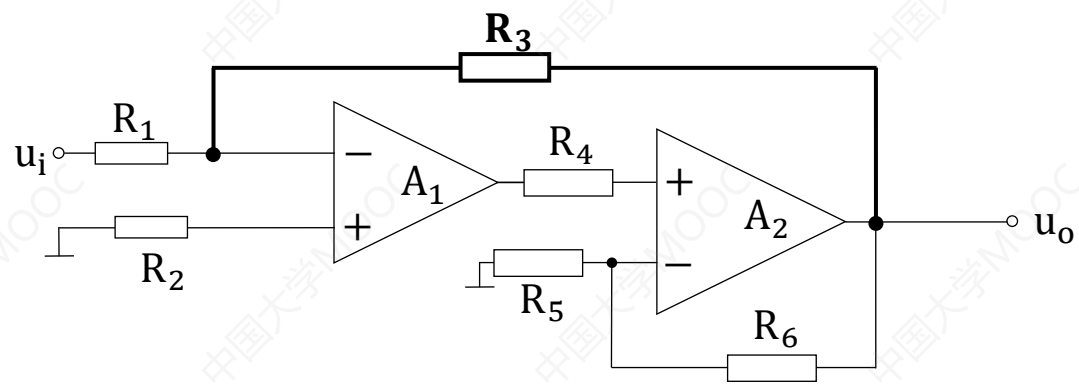


b、观察该路径是否与地直接相连



c、该路径+与他相连的地+他和地之间的部分为反馈通路

【注意：这里要找的反馈通路不能包含只横跨一个放大元件的部分】

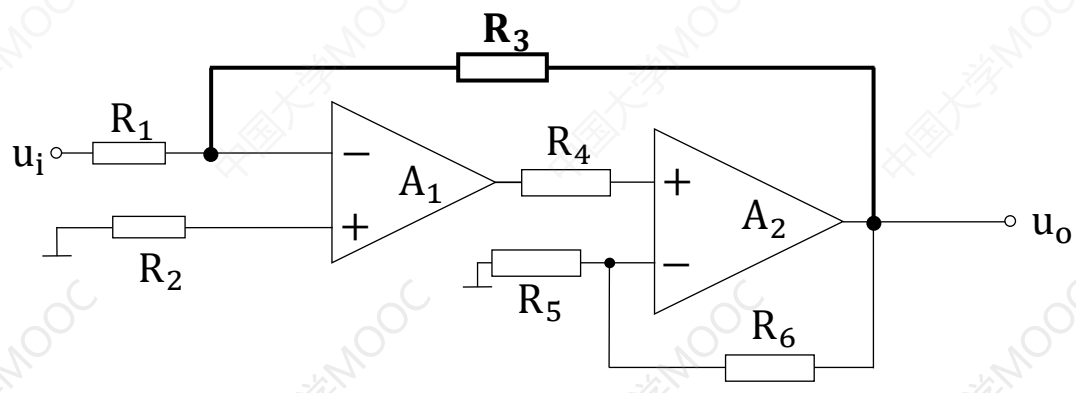


② 判断反馈为电压反馈还是电流反馈

观察反馈通路与 $\mathbf{u_o}$ 或 $\mathbf{u_o}$的“＋”之间是否只有导线

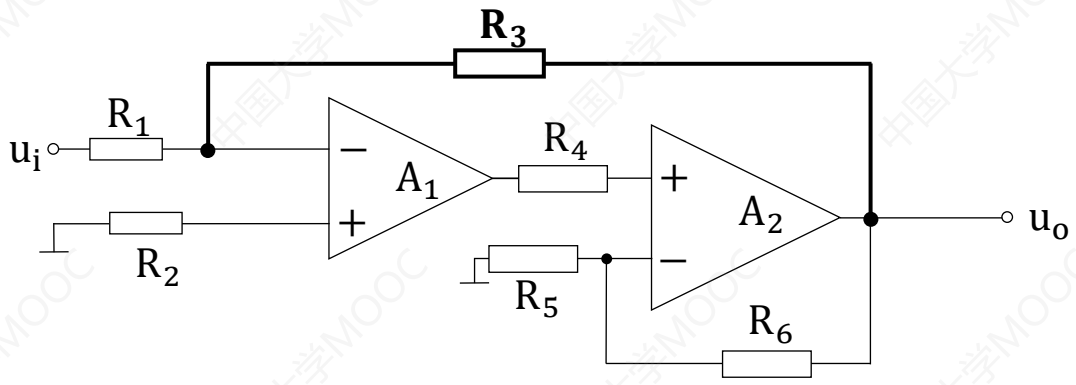
若是，则为电压反馈

若不是，则为电流反馈



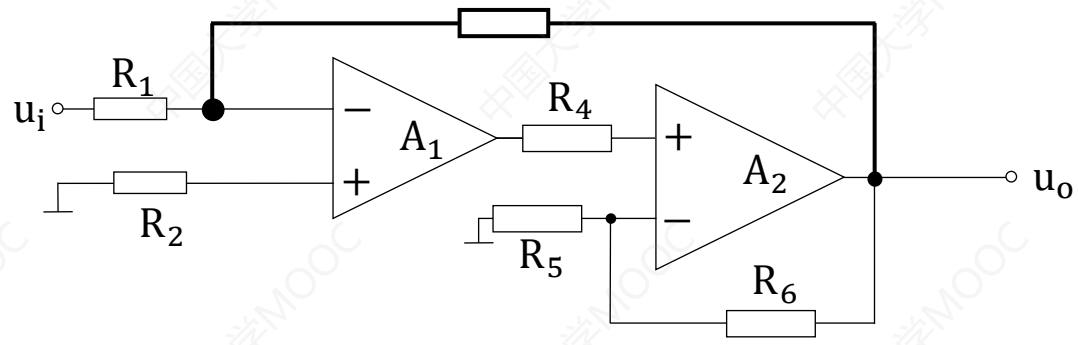
电压反馈

③ 判断反馈为串联反馈还是并联反馈



电压反馈

a、找到反馈通路与最左边放大元件输入端的交点

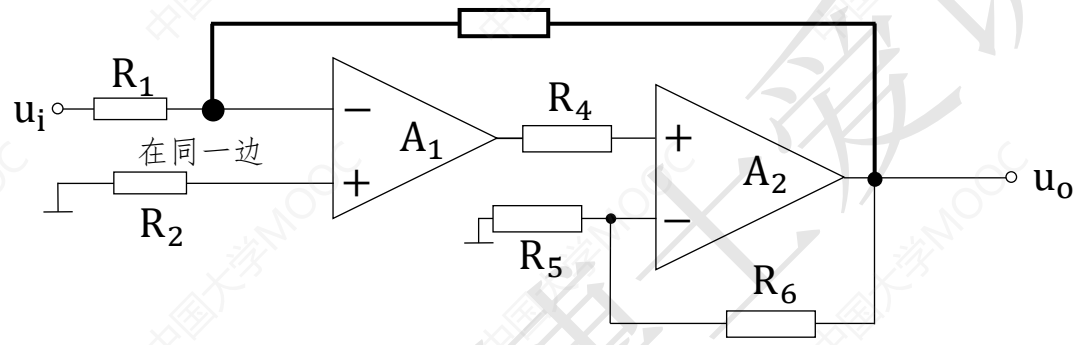


电压反馈

b、观察该交点与输入信号 u_i 是否在同一边

若该交点与输入信号 u_i 在同一边，则为并联反馈

若该交点与输入信号 u_i 不在同一边，则为串联反馈



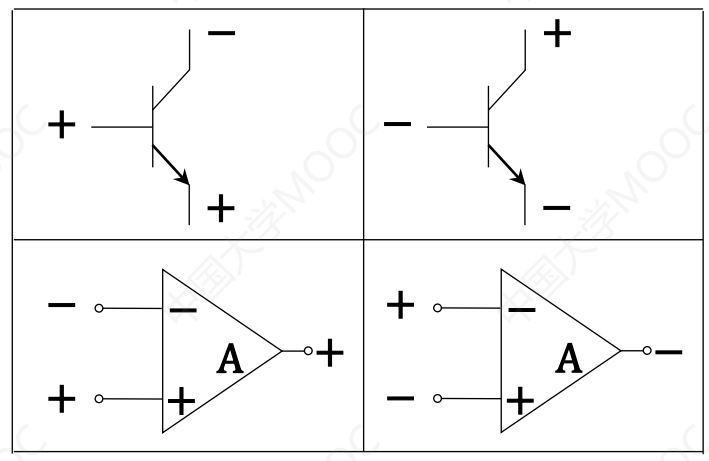
电压反馈

并联反馈

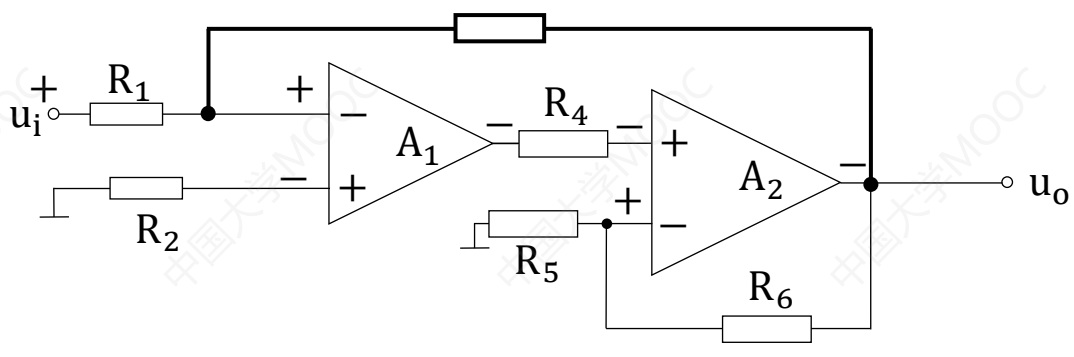
④ 判断反馈为正反馈还是负反馈

a、假设 u_i 为正，判断所有三极管和集成运放各端极性

常见的极性关系图：



【电阻、导线、电容不影响极性】

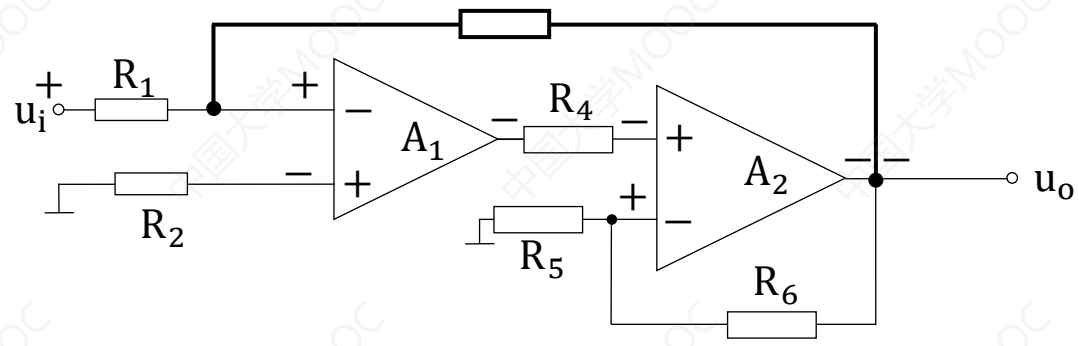


电压反馈

并联反馈

b、标出反馈通路右端的极性，判断正负反馈

并联反馈	串联反馈
极性正，正反馈 极性负，负反馈	极性正，负反馈 极性负，正反馈



电压反馈

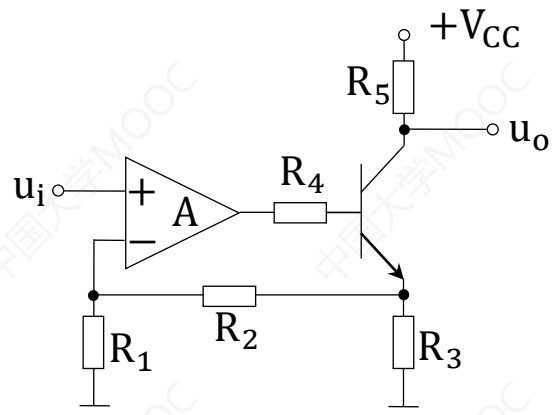
并联反馈

负反馈

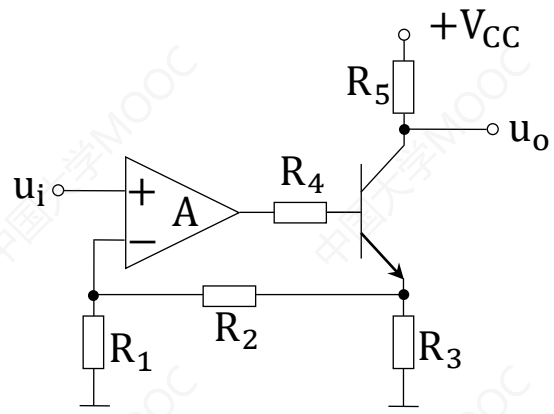
$\Longrightarrow$ 电压并联负反馈

反馈电路的计算

例1. 电路如图所示，请计算在深度负反馈条件下电路的反馈系数 $\dot{F}$ 、闭环电压放大倍数 $\dot{A}_{uf}$、闭环放大倍数 $\dot{A}_f$

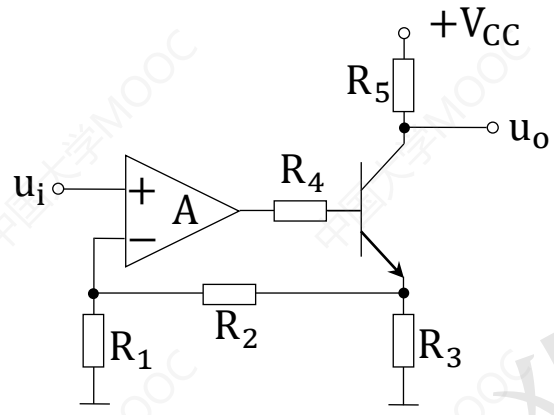


① 判断电路中的反馈组态



电流串联负反馈

详见【放大电路中的反馈】第1课【反馈组态的判断】



电流串联负反馈

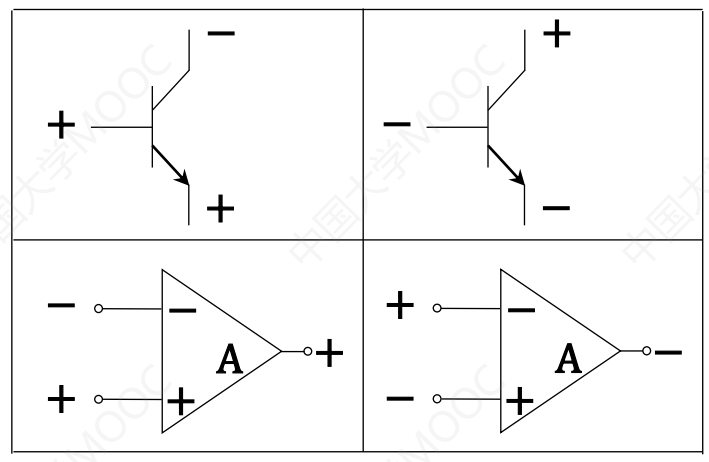
$R_b = R_5$

② 若 $\mathbf{u_i}$ 与反馈通路之间有电阻，则将该电阻记作 $\mathbf{R_a}$

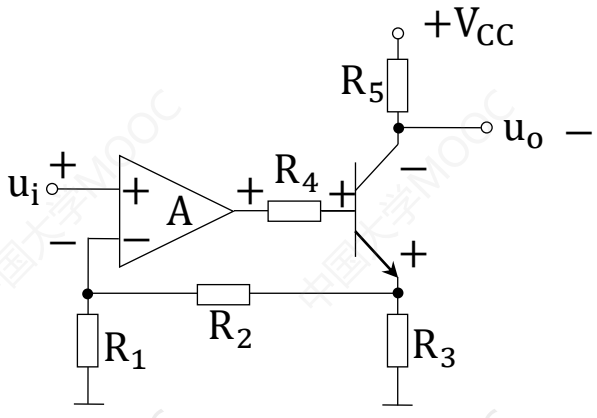
若 $\mathbf{u_o}$ 与 $\mathbf{V_{CC}}$ 之间有电阻，则将该电阻记作 $\mathbf{R_b}$

③ 假设 $\mathbf{u_i}$ 为正，判断所有三极管和集成运放各端极性及 $\mathbf{u_o}$ 的极性

常见的极性关系图：



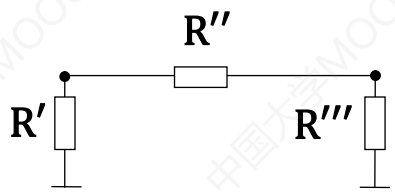
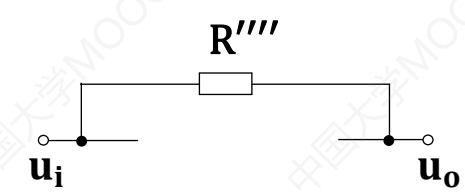
【电阻、导线、电容不影响极性】



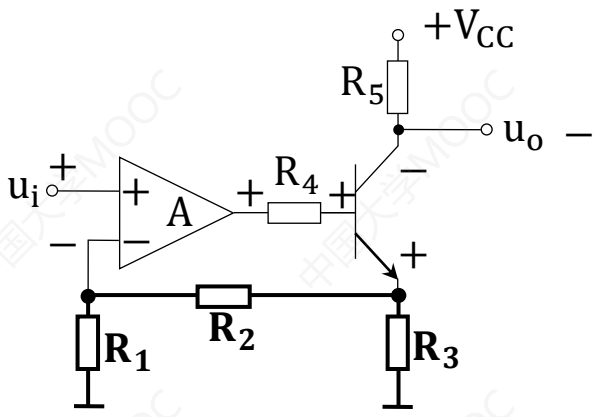
电流串联负反馈

$R_b = R_5$

④ 根据反馈通路结构和反馈组态求出 $\dot{F}$ 和 $\dot{A}_{uf}$

	
电压串联：$\dot{F}=\pm\frac{R'}{R'+R''}$ 电流串联：$\dot{F}=\pm\frac{R'R'''}{R'+R''+R'''}$	$\dot{F}=\pm\frac{1}{R''''}$
电压串联：$\dot{A}_{uf}=\pm(1+\frac{R''}{R'})$ 电流串联：$\dot{A}_{uf}=\pm\frac{R'+R''+R'''}{R'R'''}R_b$	跨两个放大元件：$\dot{A}_{uf}=\pm\frac{R''''}{R_a}$ 跨一个放大元件： $\dot{A}_{uf}=\pm\left(1+\frac{R''''}{R_a}\right)$

【u_o 为正时，取正号、u_o 为负时，取负号】



电流串联负反馈

$R_b=R_5$

$R'=R_1$

$R''=R_2$

$R'''=R_3$

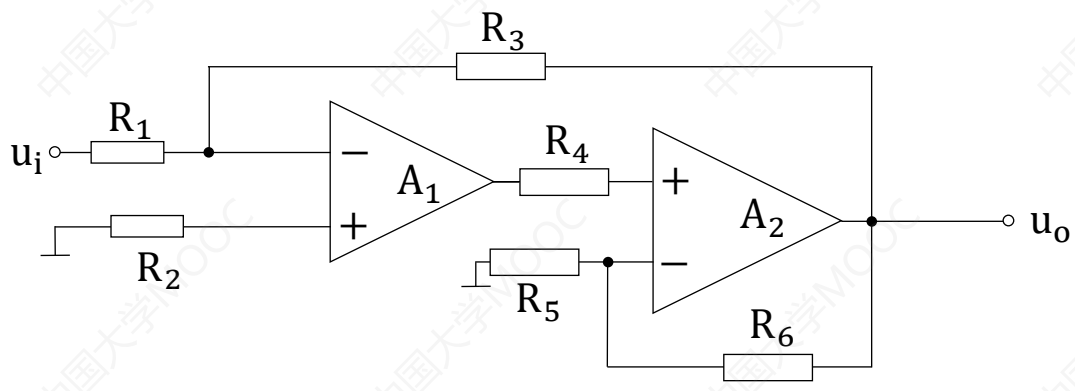
$$\dot{F}=-\frac{R'R'''}{R'+R''+R'''}=-\frac{R_1R_3}{R_1+R_2+R_3}$$

$$\dot{A}_{uf}=-\frac{R'+R''+R'''}{R'R'''}R_b=-\frac{R_1+R_2+R_3}{R_1R_3}R_5$$

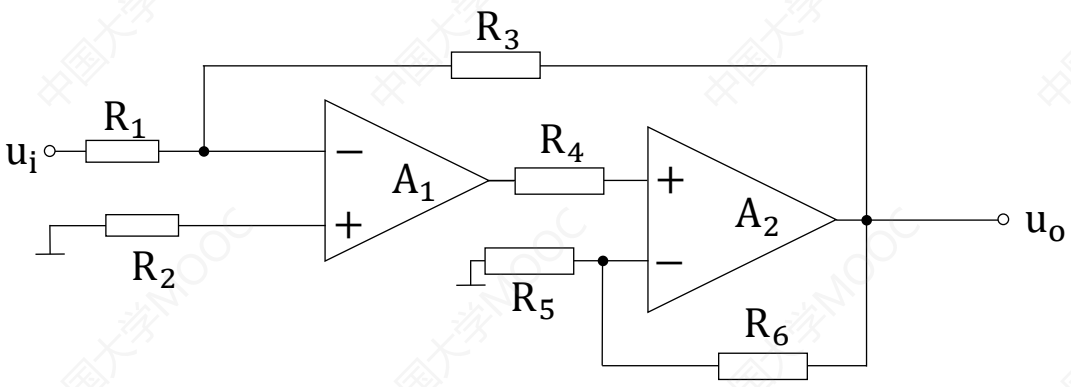
⑤ $\dot{A}_f\approx\frac{1}{\dot{F}}$

$$\dot{A}_f\approx\frac{1}{\dot{F}}=\frac{1}{-\frac{R_1R_3}{R_1+R_2+R_3}}=-\frac{R_1+R_2+R_3}{R_1R_3}$$

例2. 电路如图所示，请计算在深度负反馈条件下电路的反馈系数 $\dot{F}$、闭环电压放大倍数 $\dot{A}_{uf}$、闭环放大倍数 $\dot{A}_f$



① **判断电路中的反馈组态**

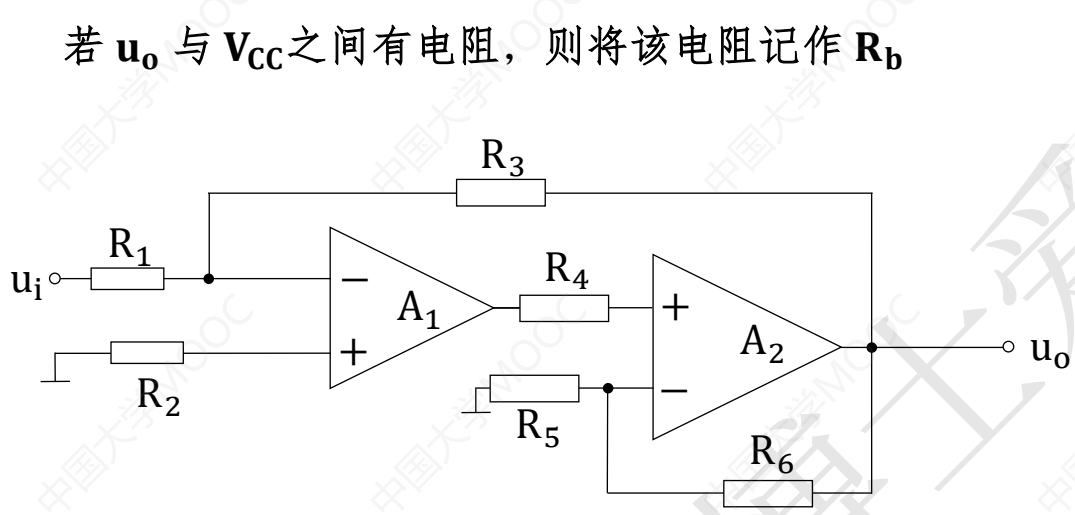


电压并联负反馈

详见【放大电路中的反馈】第1课【反馈组态的判断】

② **若 $\mathbf{u_i}$ 与反馈通路之间有电阻，则将该电阻记作 $\mathbf{R_a}$**

若 $\mathbf{u_o}$ 与 $\mathbf{V_{CC}}$ 之间有电阻，则将该电阻记作 $\mathbf{R_b}$

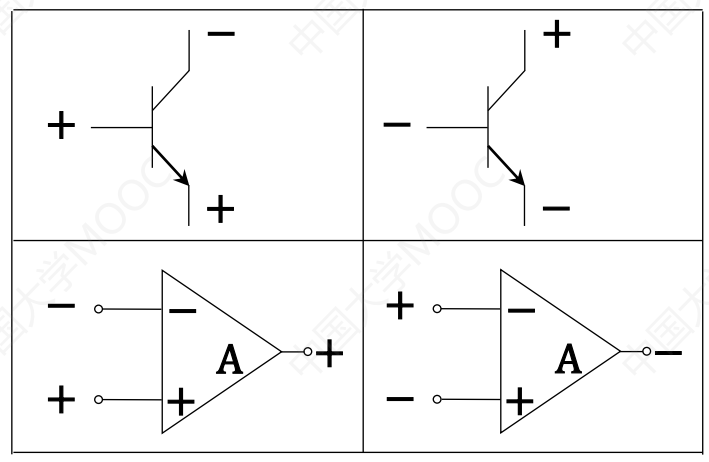


电压并联负反馈

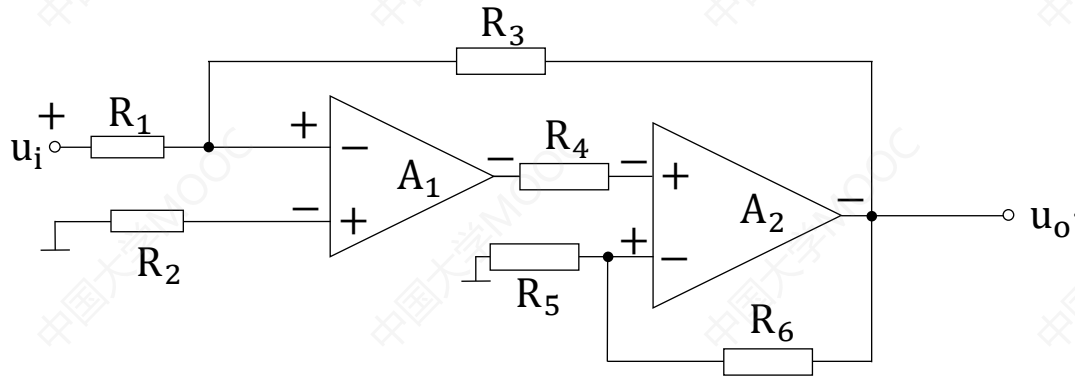
$R_a = R_1$

③ **假设 $\mathbf{u_i}$ 为正，判断所有三极管和集成运放各端极性及 $\mathbf{u_o}$ 的极性**

常见的极性关系图：



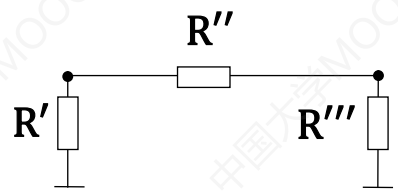
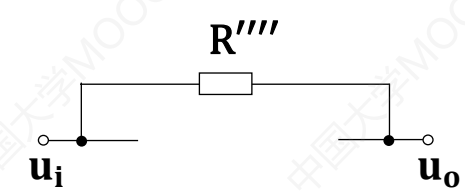
【电阻、导线、电容不影响极性】



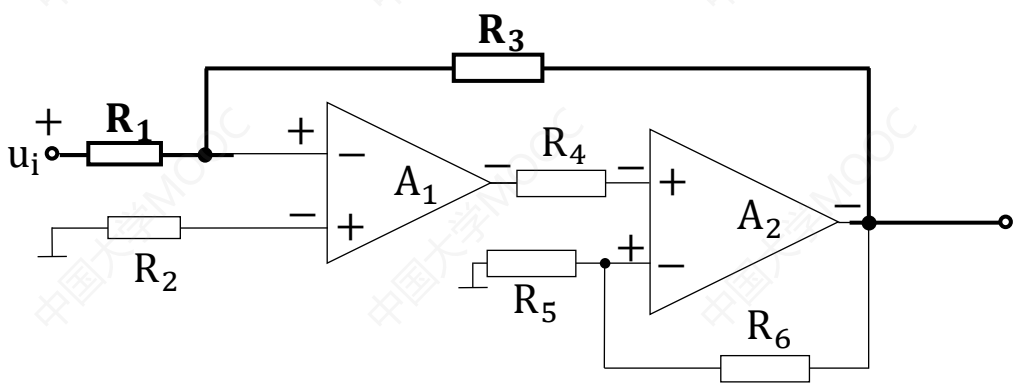
电压并联负反馈

$R_a = R_1$

④ 根据反馈通路结构和反馈组态求出 $\dot{F}$ 和 $\dot{A}_{uf}$

	
电压串联：$\dot{F}=\pm\frac{R'}{R'+R''}$ 电流串联：$\dot{F}=\pm\frac{R'R'''}{R'+R''+R'''}$	$\dot{F}=\pm\frac{1}{R''''}$
电压串联：$\dot{A}_{uf}=\pm(1+\frac{R''}{R'})$ 电流串联：$\dot{A}_{uf}=\pm\frac{R'+R''+R'''}{R'R'''}R_b$	跨两个放大元件：$\dot{A}_{uf}=\pm\frac{R''''}{R_a}$ 跨一个放大元件： $\dot{A}_{uf}=\pm\left(1+\frac{R''''}{R_a}\right)$

【u_o 为正时，取正号、u_o 为负时，取负号】



$R_a = R_1$

$R'''' = R_3$

$\dot{F} = -\frac{1}{R''''} = -\frac{1}{R_3}$

$\dot{A}_{uf} = -\frac{R''''}{R_a} = -\frac{R_3}{R_1}$

⑤ $\dot{A}_f \approx \frac{1}{\dot{F}}$

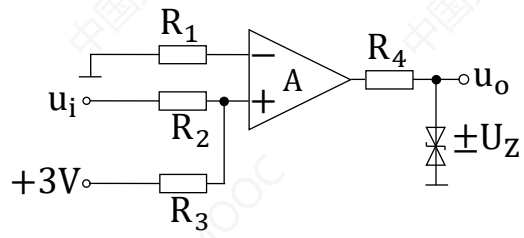
$\dot{A}_f \approx \frac{1}{\dot{F}} = \frac{1}{-\frac{1}{R_3}} = -R_3$

单限电压比较器

例1. 电路如图所示，$R_1=R_2=R_3=R_4$，$U_Z=8V$，则

(1) 画出电压传输特性曲线

(2) 若输入信号 u_i 如“图1”，试画出输出电压u_o的波形图



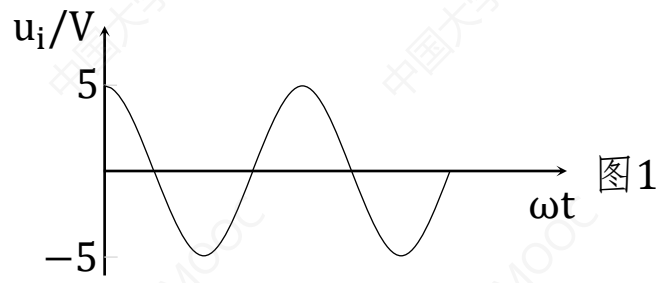
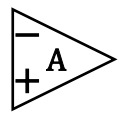
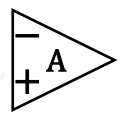
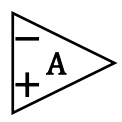
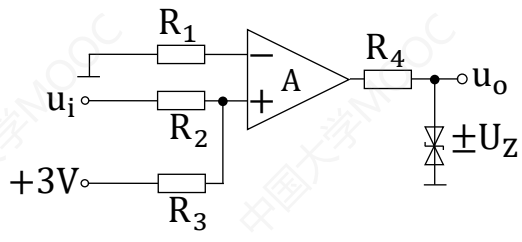


图1

① 将 u_i 与“  ”之间干路上的电阻记作 R_a

将 u_i 与“  ”之间支路上的电阻记作 R_b

将 u_i 与“  ”之间支路上的电压记作U_{REF}



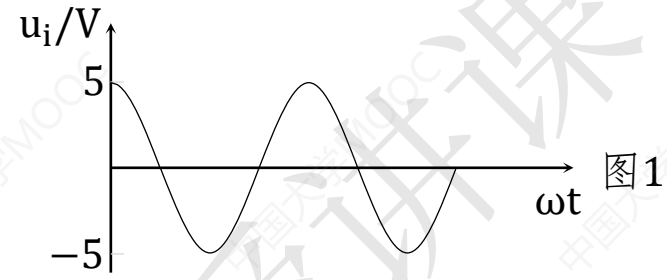


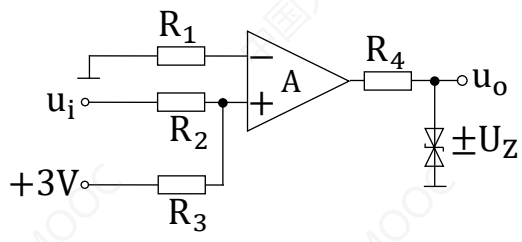
图1

$R_a = R_2$

$R_b = R_3$

$U_{REF} = 3V$

② $U_T = -\frac{R_a}{R_b} U_{REF}$



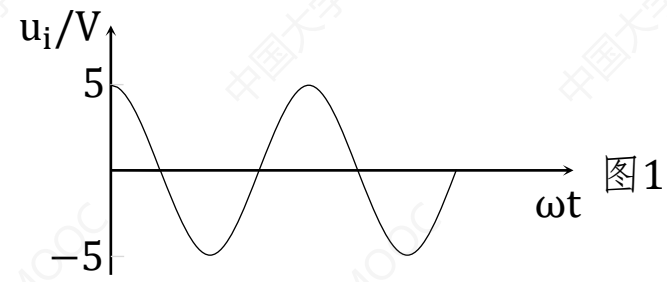


图1

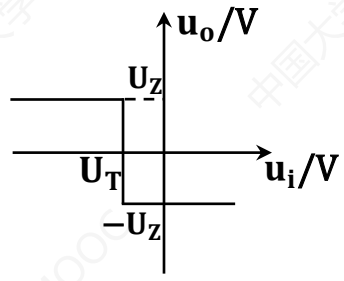
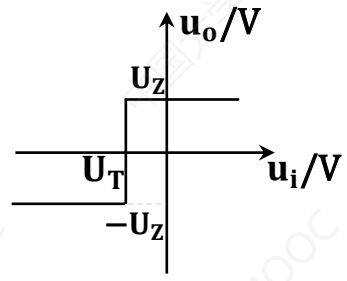
$R_a = R_2$

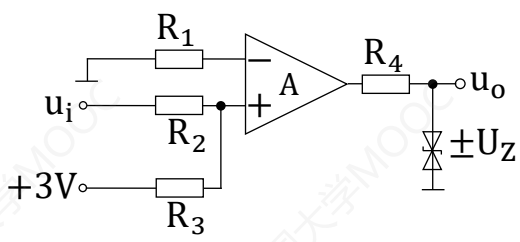
$R_b = R_3$

$U_{REF} = 3V$

$$U_T = -\frac{R_a}{R_b} U_{REF}$$
$$= -\frac{R_2}{R_3} \cdot 3V$$
$$= -3V$$

③ 画出特性曲线

u_i 在“−”的一端	u_i 在“+”的一端
	



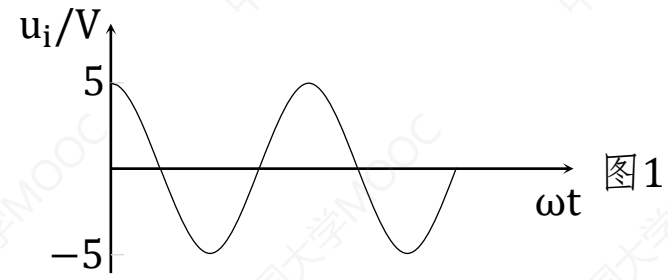


图1

$R_a = R_2$

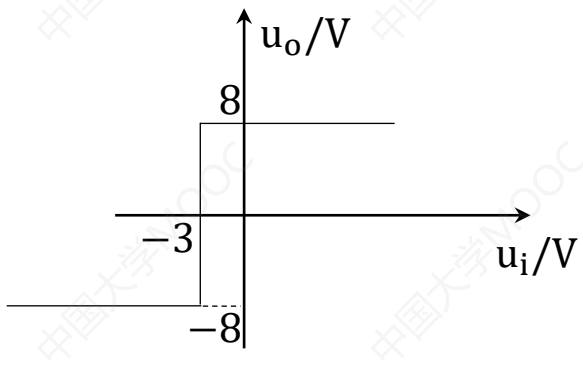
$R_b = R_3$

$U_{REF} = 3V$

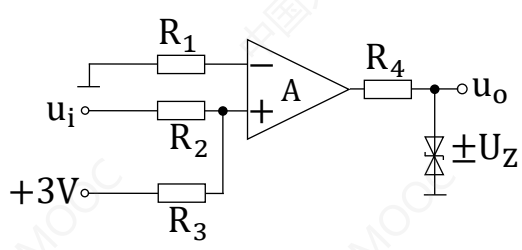
$$U_T = -\frac{R_a}{R_b} U_{REF}$$

$$= -\frac{R_2}{R_3} \cdot 3V$$

$$= -3V$$



④ 写出 $u_i < U_T$ 时， u_o 的取值、$u_i > U_T$ 时， u_o 的取值



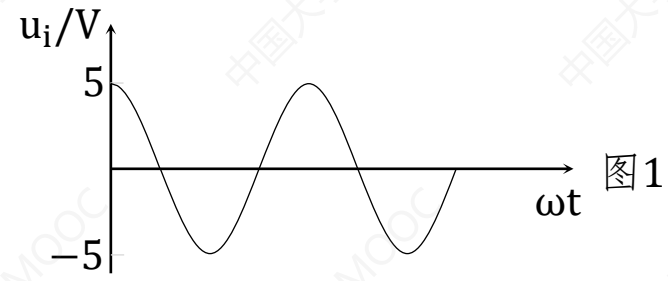


图1

$R_a = R_2$

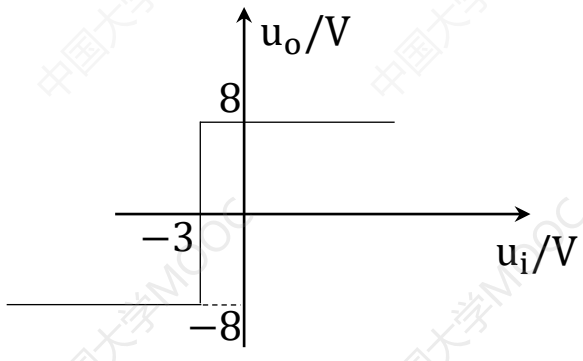
$R_b = R_3$

$U_{REF} = 3V$

$$U_T = -\frac{R_a}{R_b} U_{REF}$$

$$= -\frac{R_2}{R_3} \cdot 3V$$

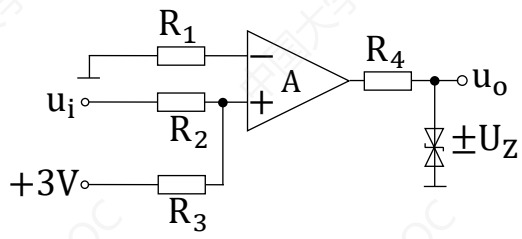
$$= -3V$$



$u_i < -3V$时， $u_o = -8V$

$u_i > -3V$时， $u_o = 8V$

⑤ 根据输入信号 $\mathbf{u_i}$ 的图像画 $\mathbf{u_o}$ 的波形图



$R_a = R_2$

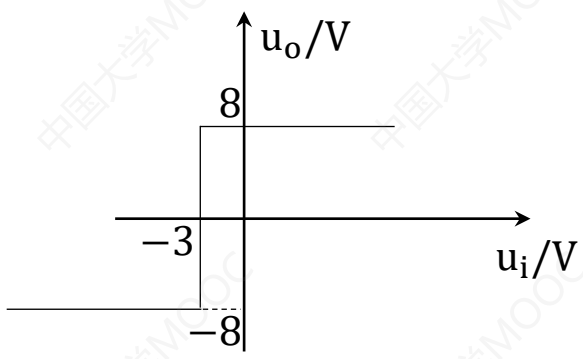
$R_b = R_3$

$U_{REF} = 3V$

$$U_T = -\frac{R_a}{R_b} U_{REF}$$

$$= -\frac{R_2}{R_3} \cdot 3V$$

$$= -3V$$



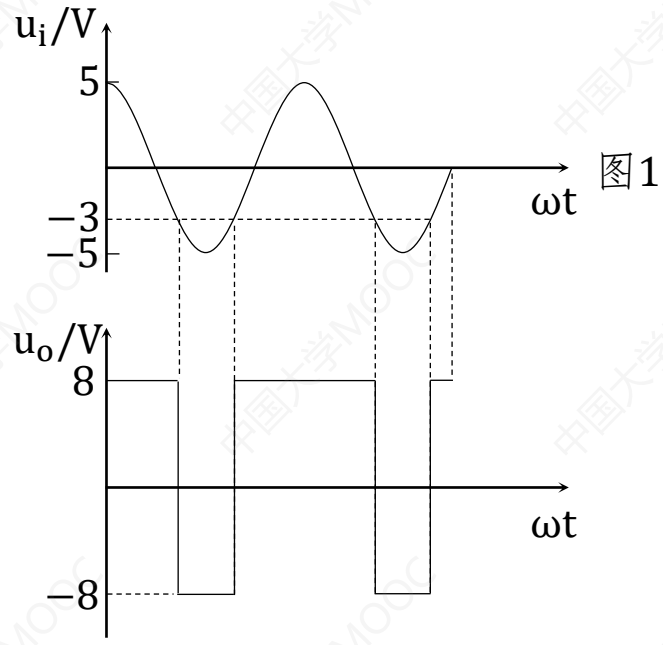


图1

$u_i < -3V$时，$u_o = -8V$

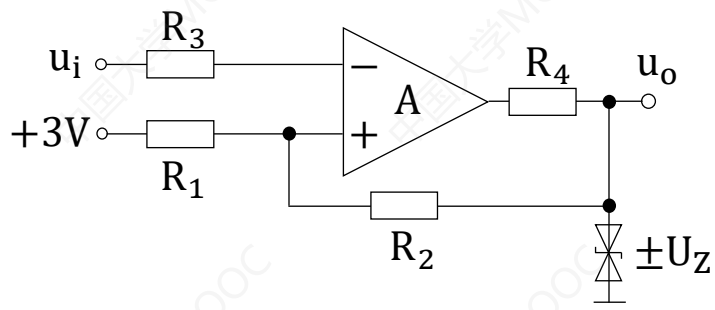
$u_i > -3V$时，$u_o = 8V$

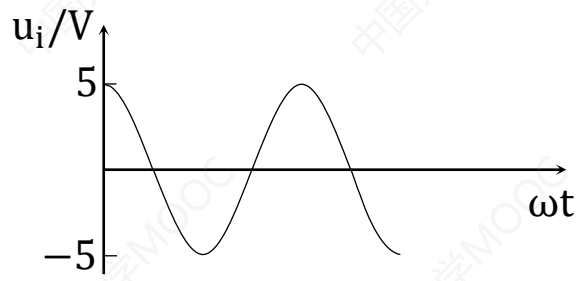
滞回电压比较器

例1. 电路如图所示，$R_1=R_3=10k\Omega$，$R_2=R_4=20k\Omega$，$U_Z=6V$

(1) 画出电压传输特性曲线

(2) 若输入信号 u_i 的图像如右图，试画出输出电压 u_o 的波形图

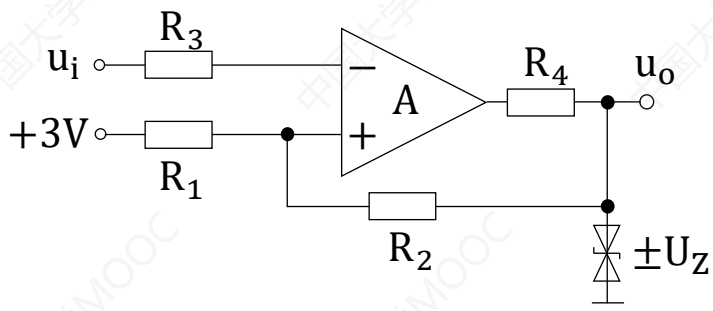


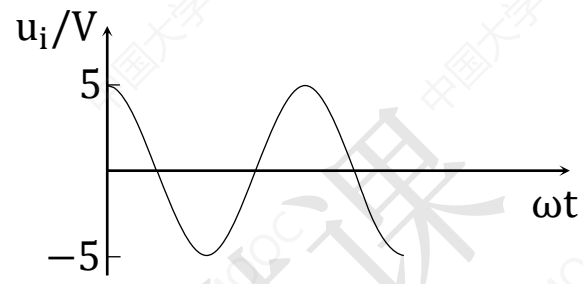


① 将横跨三角形支路上的电阻记作 $\mathbf{R_a}$

将与支路相连的输入端上的电阻记作 $\mathbf{R_b}$

将输入端 $\mathbf{u_i}$ 之外的电压记作 $\mathbf{U_{REF}}$





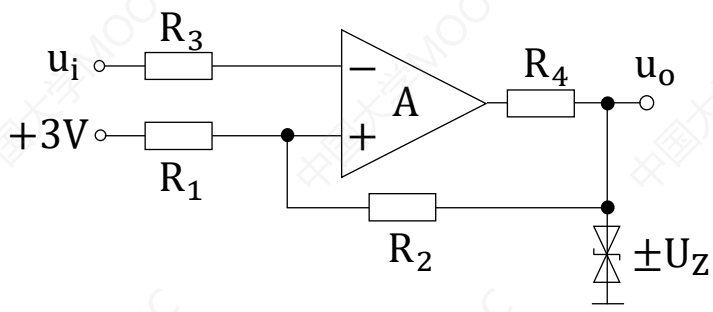
$R_a = R_2 = 20k\Omega$

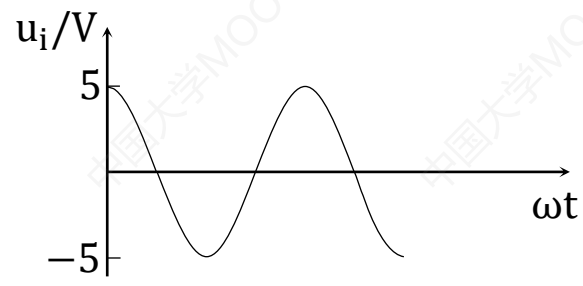
$R_b = R_1 = 10k\Omega$

$U_{REF} = 3V$

② 求 $\mathbf{U_{T1}}$、$\mathbf{U_{T2}}$

$\mathbf{u_i}$ 在“−”的一端	$\mathbf{U_{T1}=\frac{R_a}{R_a+R_b}U_{REF}-\frac{R_b}{R_a+R_b}U_Z}$
	$\mathbf{U_{T2}=\frac{R_a}{R_a+R_b}U_{REF}+\frac{R_b}{R_a+R_b}U_Z}$
$\mathbf{u_i}$ 在“+”的一端	$\mathbf{U_{T1}=U_{REF}+\frac{R_b}{R_a}(U_{REF}-U_Z)}$
	$\mathbf{U_{T2}=U_{REF}+\frac{R_b}{R_a}(U_{REF}+U_Z)}$





$R_a = R_2 = 20k\Omega$

$R_b = R_1 = 10k\Omega$

$U_{REF} = 3V$

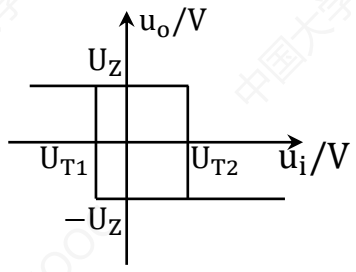
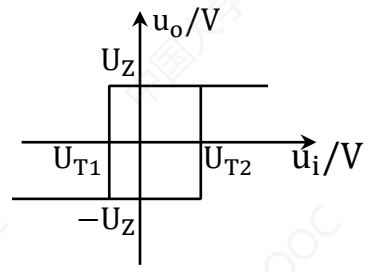
$$U_{T1}=\frac{R_a}{R_a+R_b}U_{REF}-\frac{R_b}{R_a+R_b}U_Z=\frac{20k\Omega}{20k\Omega+10k\Omega}\times 3V-\frac{10k\Omega}{20k\Omega+10k\Omega}\times 6V$$

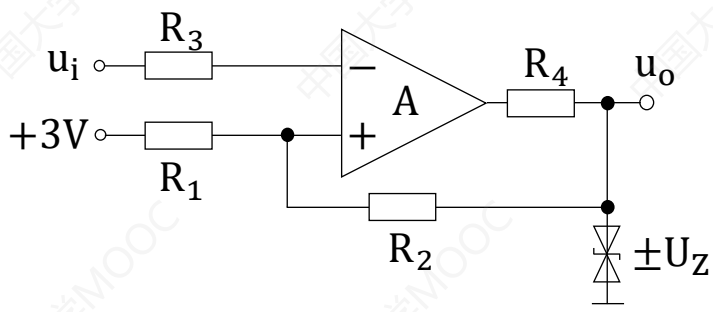
$$=\frac{20k\Omega}{30k\Omega}\times 3V-\frac{10k\Omega}{30k\Omega}\times 6V=\frac{2}{3}\times 3V-\frac{1}{3}\times 6V=2V-2V=0V$$

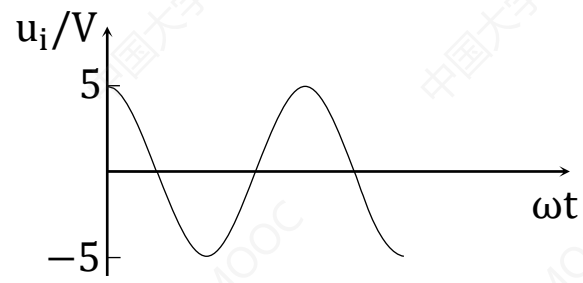
$$U_{T2}=\frac{R_a}{R_a+R_b}U_{REF}+\frac{R_b}{R_a+R_b}U_Z=\frac{20k\Omega}{20k\Omega+10k\Omega}\times 3V+\frac{10k\Omega}{20k\Omega+10k\Omega}\times 6V$$

$$=\frac{20k\Omega}{30k\Omega}\times 3V+\frac{10k\Omega}{30k\Omega}\times 6V=\frac{2}{3}\times 3V+\frac{1}{3}\times 6V=2V+2V=4V$$

③ 画出特性曲线

u_i 在“−”的一端	u_i 在“+”的一端
	





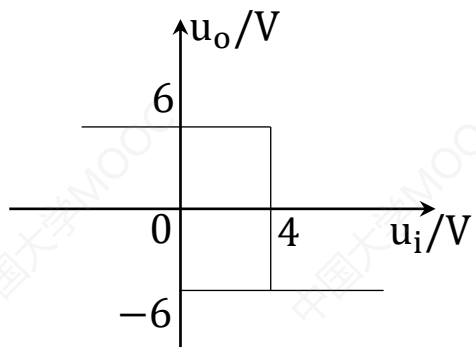
$R_a = R_2 = 20k\Omega$

$R_b = R_1 = 10k\Omega$

$U_{REF} = 3V$

$U_{T1} = 0V$

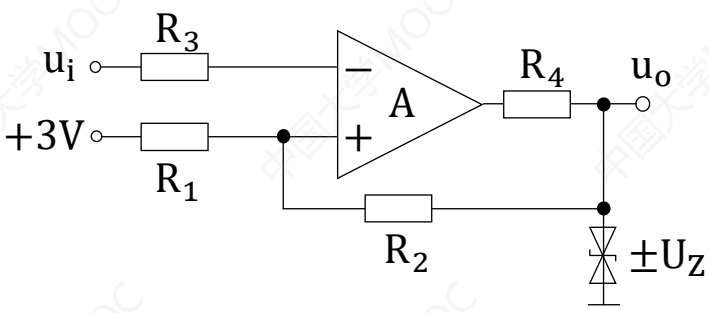
$U_{T2} = 4V$

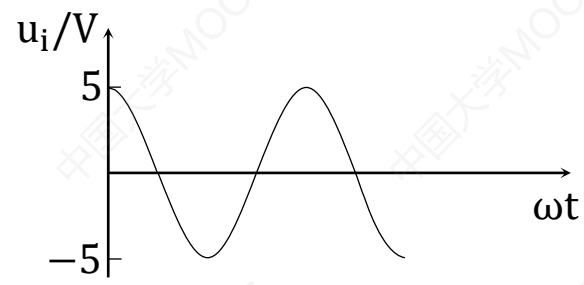


④ 画 u_o 的波形图

a、判断 u_i 在不同范围内， u_o 的取值

u_i 在“−”的一端	u_i 在“+”的一端
$u_i < U_{T1}$： $u_o = U_Z$	$u_i < U_{T1}$： $u_o = -U_Z$
$u_i > U_{T2}$： $u_o = -U_Z$	$u_i > U_{T2}$： $u_o = U_Z$
$U_{T1} < u_i < U_{T2}$：	$U_{T1} < u_i < U_{T2}$：
$\begin{cases} u_i \text{图像“↑”} & u_o = U_Z \\ u_i \text{图像“↓”} & u_o = -U_Z \end{cases}$	$\begin{cases} u_i \text{图像“↑”} & u_o = -U_Z \\ u_i \text{图像“↓”} & u_o = U_Z \end{cases}$





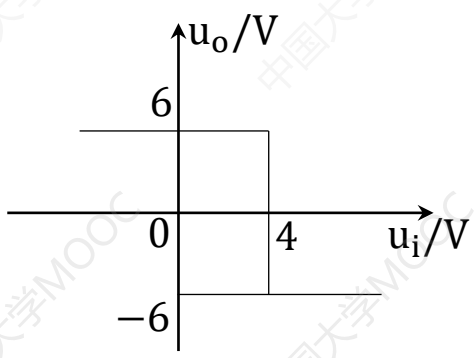
$R_a = R_2 = 20k\Omega$

$R_b = R_1 = 10k\Omega$

$U_{REF} = 3V$

$U_{T1} = 0V$

$U_{T2} = 4V$



$\Rightarrow$

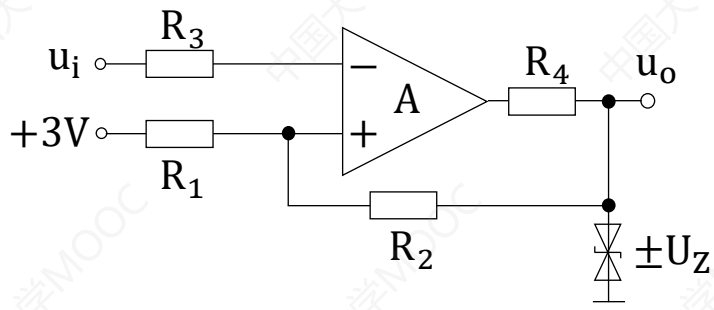
$u_i < 0V$： $u_o = 6V$

$u_i > 4V$： $u_o = -6V$

$0V < u_i < 4V$：

$\begin{cases} u_i \text{图像“↑”} & u_o = 6V \\ u_i \text{图像“↓”} & u_o = -6V \end{cases}$

b、根据输入信号 u_i 的图像画 u_o 的波形图



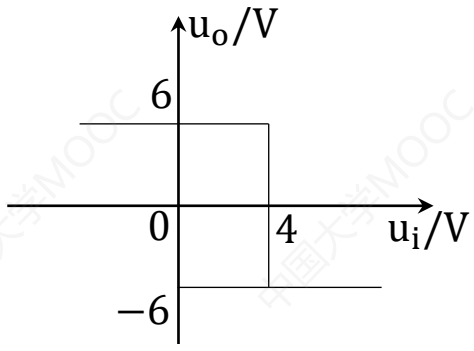
$R_a = R_2 = 20k\Omega$

$R_b = R_1 = 10k\Omega$

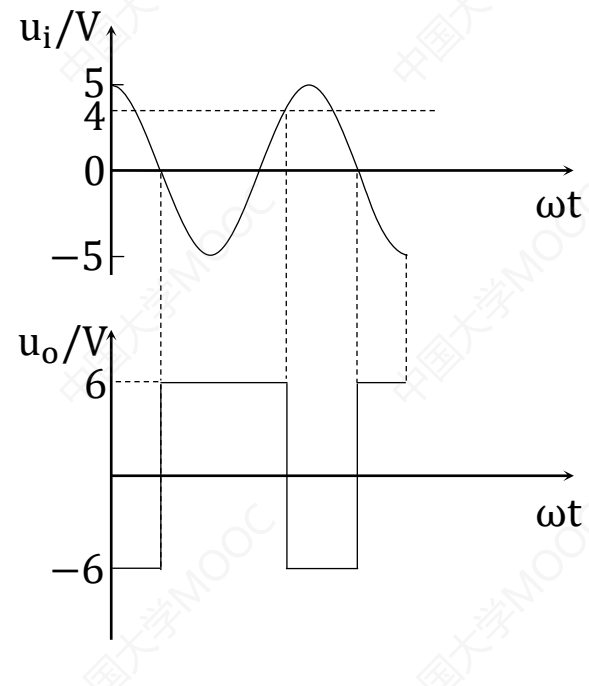
$U_{REF} = 3V$

$U_{T1} = 0V$

$U_{T2} = 4V$



$\Rightarrow$



$u_i < 0V$：$u_o = 6V$

$u_i > 4V$：$u_o = -6V$

$0V < u_i < 4V$：

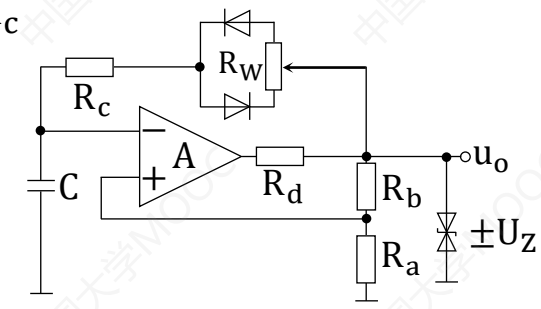
$$\begin{cases} u_i \text{图像“}\uparrow\text{”} & u_o = 6V \\ u_i \text{图像“}\downarrow\text{”} & u_o = -6V \end{cases}$$

非正弦波发生电路

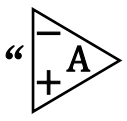
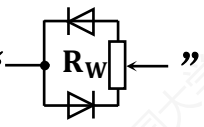
例1. 已知某电路如图所示，其中，$U_Z = 6V$，$R_b = 2R_a$，滑动变阻器 R_W 位于中间位置，$R_W = 2R_c$

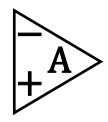
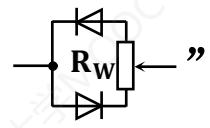
(1) 试求出电路的频率、占空比

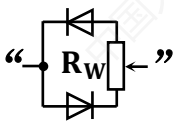
(2) 试画出 u_o 以及 u_C 的波形图

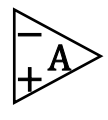
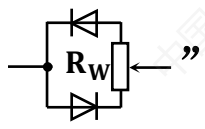


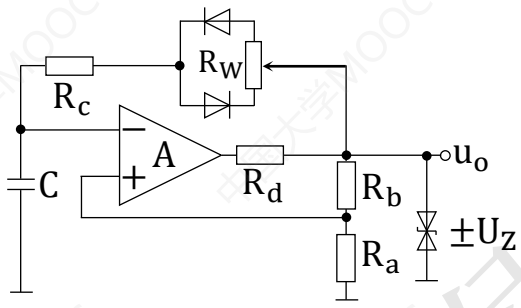
① 判断电路类型

矩形波发生电路：只有一个“  ”且没有“  ”

占空比可调矩形波发生电路：{只有一个“  ”；且有“  ”}

方波—三角波发生电路：有两个“  ”且无“  ”

锯齿波发生电路：{有两个“  ”；且有“  ”}



占空比可调矩形波发生电路

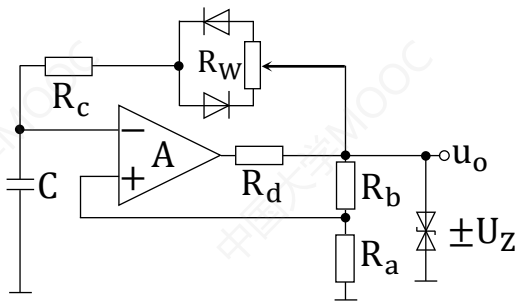
② 计算相关的参数

矩形波发生电路

占空比可调矩形波发生电路

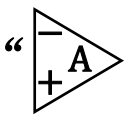
方波—三角波发生电路

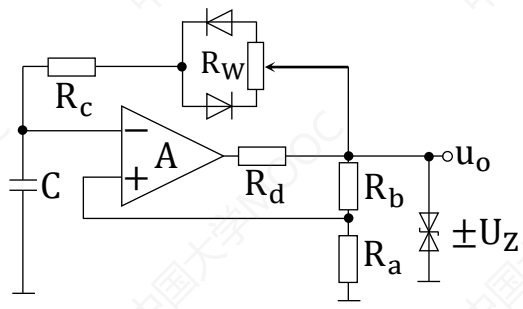
锯齿波发生电路



占空比可调矩形波发生电路

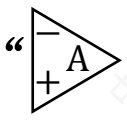
占空比可调矩形波发生电路

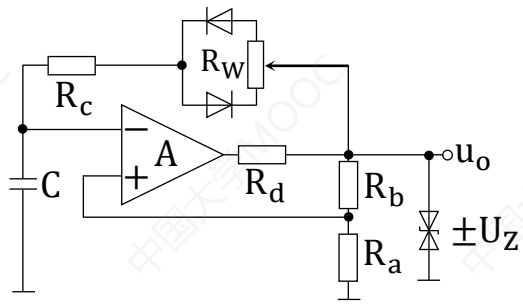
a、将“  ”的“+”与“⊥”直接相连的电阻记作$\mathbf{R_1}$



占空比可调矩形波发生电路

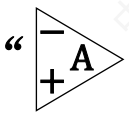
(1) $R_1 = R_a$

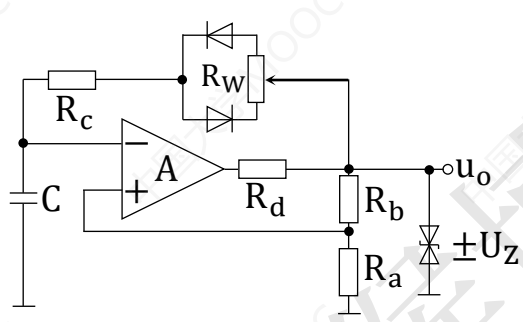
b、将“  ”的“+”与“⊥”之间的电阻记作$\mathbf{R_2}$



占空比可调矩形波发生电路

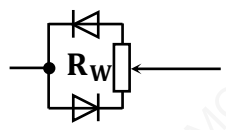
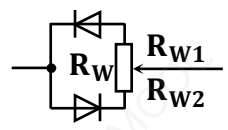
(1) $R_1 = R_a$、$R_2 = R_b$

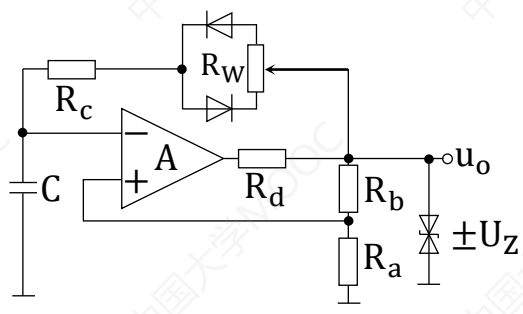
c、将“  ”的“−”与“$\mathbf{u_o}$”之间的普通电阻记作$\mathbf{R_3}$



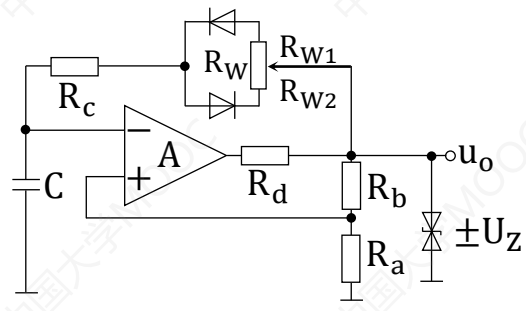
占空比可调矩形波发生电路

(1) $R_1 = R_a$、$R_2 = R_b$、$R_3 = R_c$

d、将“  ”变成“  ”



占空比可调矩形波发生电路



(1) $R_1 = R_a$、$R_2 = R_b$、$R_3 = R_c$

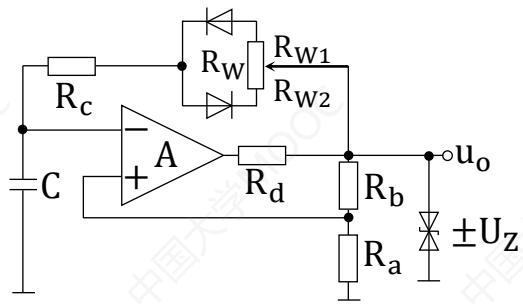
$$R_{W1} = R_{W2} = \frac{R_W}{2} = \frac{2R_c}{2} = R_c$$

e、电压幅值 $U_T=\frac{R_1}{R_1+R_2}U_Z$

高电平时间 $T_1=(R_{W1}+R_3)C\ln\left(1+\frac{2R_1}{R_2}\right)$

低电平时间 $T_2=(R_{W2}+R_3)C\ln\left(1+\frac{2R_1}{R_2}\right)$

周期 $T=T_1+T_2$、占空比 $q=\frac{R_{W1}+R_3}{R_W+2R_3}$、频率 $f=\frac{1}{T}$



占空比可调矩形波发生电路

(1) $R_1=R_a$、$R_2=R_b$、$R_3=R_c$

$$R_{W1}=R_{W2}=\frac{R_W}{2}=\frac{2R_c}{2}=R_c$$

电压幅值 $U_T=\frac{R_1}{R_1+R_2}U_Z$

$$=\frac{R_a}{R_a+R_b}\cdot 6V$$

$$=\frac{R_a}{R_a+2R_a}\cdot 6V$$

$$=\frac{R_a}{3R_a}\cdot 6V$$

$$=\frac{1}{3}\cdot 6V$$

$$=2V$$

高电平时间 $T_1=(R_{W1}+R_3)C\ln\left(1+\frac{2R_1}{R_2}\right)$

$$=(R_c+R_c)C\ln\left(1+\frac{2R_a}{R_b}\right)$$

$$=2R_cC\ln\left(1+\frac{R_b}{R_b}\right)$$

$$=2R_cC\ln(1+1)$$

$$=2R_cC\ln2$$

低电平时间 $T_2=(R_{W2}+R_3)C\ln\left(1+\frac{2R_1}{R_2}\right)$

$$=(R_c+R_c)C\ln\left(1+\frac{2R_a}{R_b}\right)$$

$$=2R_cC\ln\left(1+\frac{R_b}{R_b}\right)$$

$$=2R_cC\ln(1+1)$$

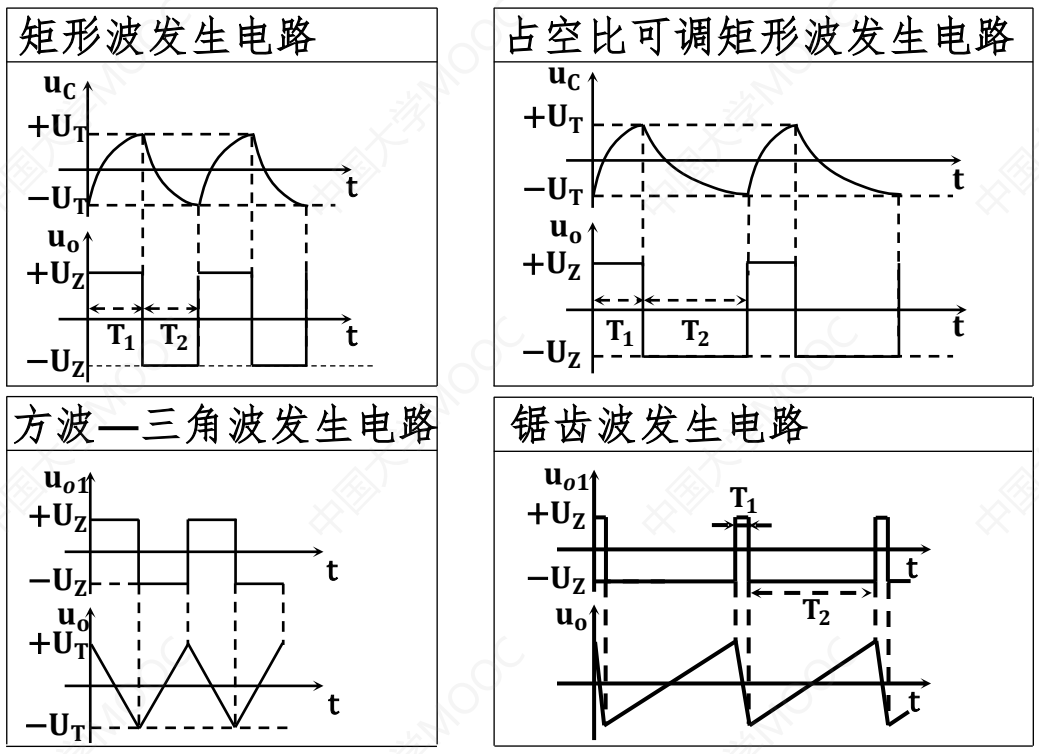
$$=2R_cC\ln2$$

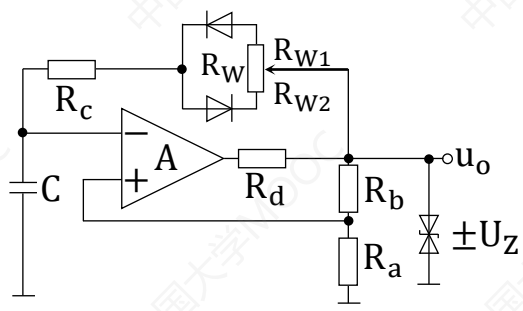
周期 $T=T_1+T_2=2R_cC\ln2+2R_cC\ln2=4R_cC\ln2$

占空比 $q=\frac{R_{W1}+R_3}{R_W+2R_3}=\frac{R_c+R_c}{2R_c+2R_c}=\frac{2R_c}{4R_c}=\frac{1}{2}$

频率 $f=\frac{1}{T}=\frac{1}{4R_cC\ln2}$

③ 画波形图





占空比可调矩形波发生电路

(1) $R_1 = R_a$、$R_2 = R_b$、$R_3 = R_c$

$$R_{W1} = R_{W2} = \frac{R_W}{2} = \frac{2R_c}{2} = R_c$$

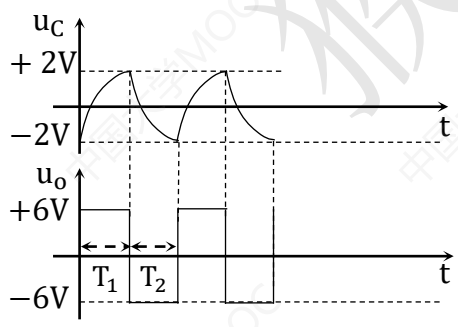
电压幅值 $U_T = 2V$

高电平时间 $T_1 = 2R_cCln2$、低电平时间 $T_2 = 2R_cCln2$

周期 $T = T_1 + T_2 = 2R_cCln2 + 2R_cCln2 = 4R_cCln2$

占空比 $q = \frac{R_{W1}+R_3}{R_W+2R_3} = \frac{R_c+R_c}{2R_c+2R_c} = \frac{2R_c}{4R_c} = \frac{1}{2}$

频率 $f = \frac{1}{T} = \frac{1}{4R_cCln2}$

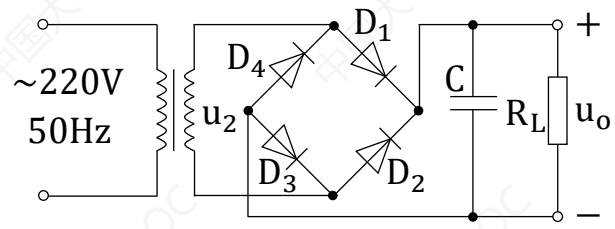


整流、滤波电路

例1. 电路如图所示，R_L=40Ω，C=1000μF，交流电压有效值 u_2=20V，则

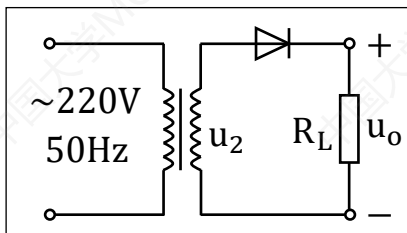
(1) 求输出电压平均值、输出电流平均值，二极管最大平均电流
二极管最大反向电压、电容耐压值

(2) 若电容开焊，且考虑电压波动，求二极管最大反向电压

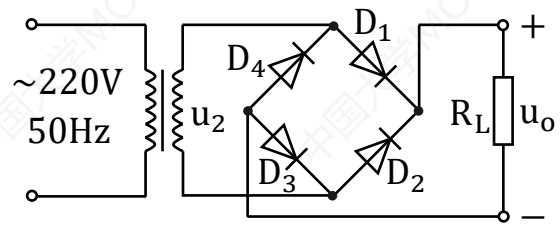


(1) 求输出电压平均值、输出电流平均值，二极管最大平均电流
二极管最大反向电压

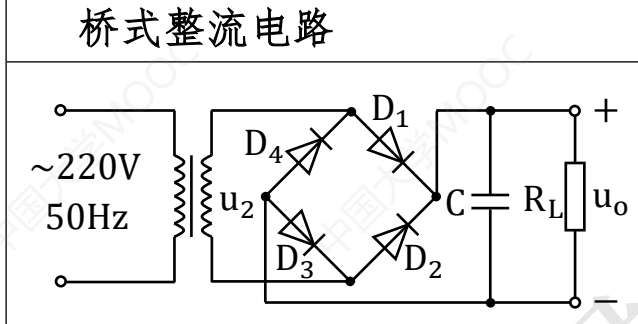
① 判断电路类型



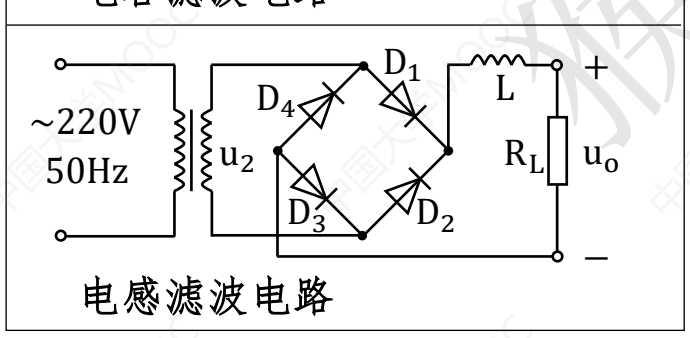
半波整流电路



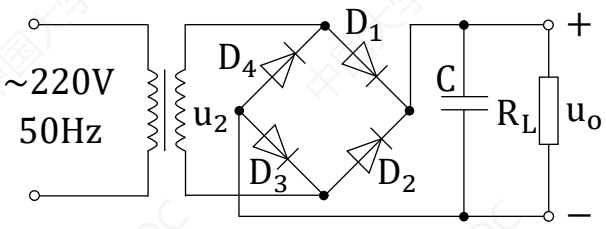
桥式整流电路



电容滤波电路

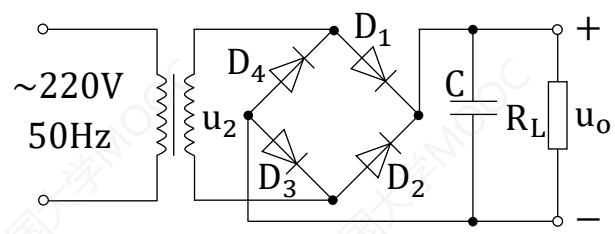


电感滤波电路



电容滤波电路

② 将变压器中，靠近 u_o 侧的电压记作 U_2



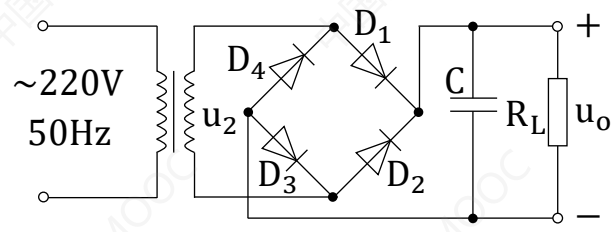
电容滤波电路

(1) U_2= u_2=20V

③ 根据电路的类型套公式求参数

桥式整流电路： 输出电压平均值 $\mathbf{U_O = 0.9U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$
电容滤波电路： 输出电压平均值 $\mathbf{U_O = 1.2U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$、电容耐压值 $\mathbf{U_C = 1.1\sqrt{2}U_2}$
电感滤波电路： 输出电压平均值 $\mathbf{U_O = 0.9\,U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$
半波整流电路： 输出电压平均值 $\mathbf{U_O = 0.45U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = 1.1 I_O}$
四种类型共用：二极管最大反向电压 $\mathbf{U_{Rmax} = 1.1\sqrt{2}U_2}$

【注意：若题干没提电压波动，则将 1.1 变为 1】



电容滤波电路

(1) $U_2 = u_2 = 20V$

输出电压平均值 $U_O = 1.2U_2 = 1.2 \times 20V = 24V$

输出电流平均值 $I_O = \frac{U_O}{R_L} = \frac{24V}{40\Omega} = 0.6A$

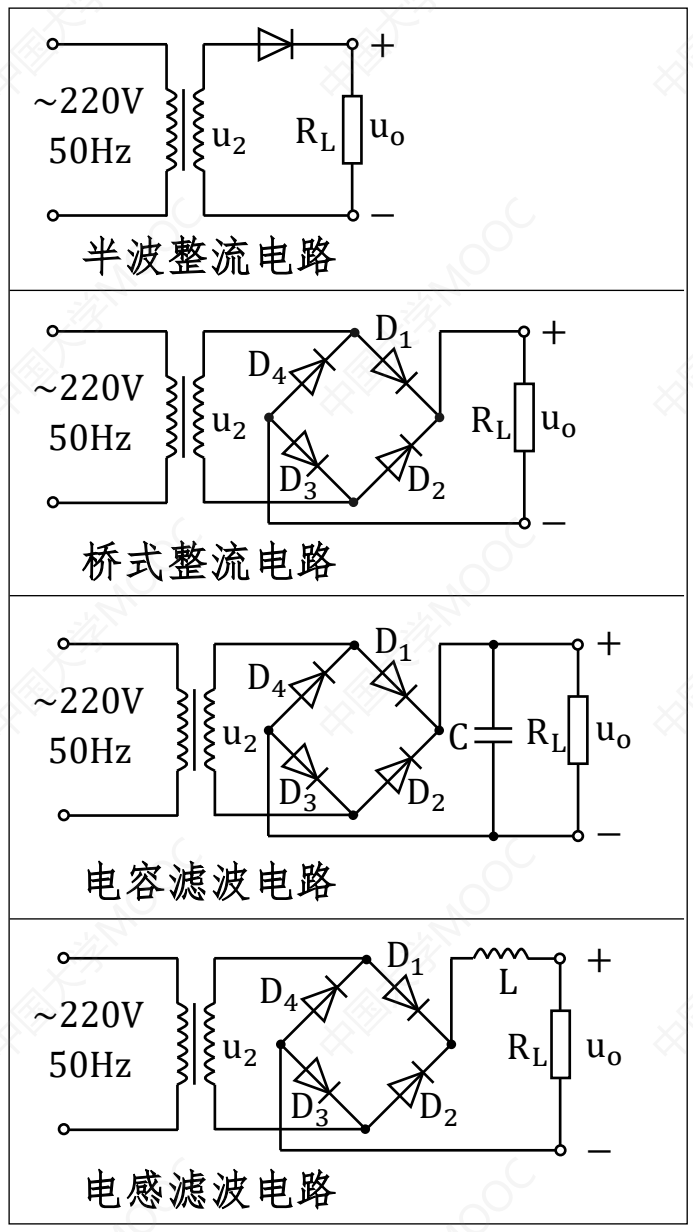
二极管最大平均电流 $I_D = \frac{1}{2} I_O = \frac{1}{2} \times 0.6A = 0.3A$

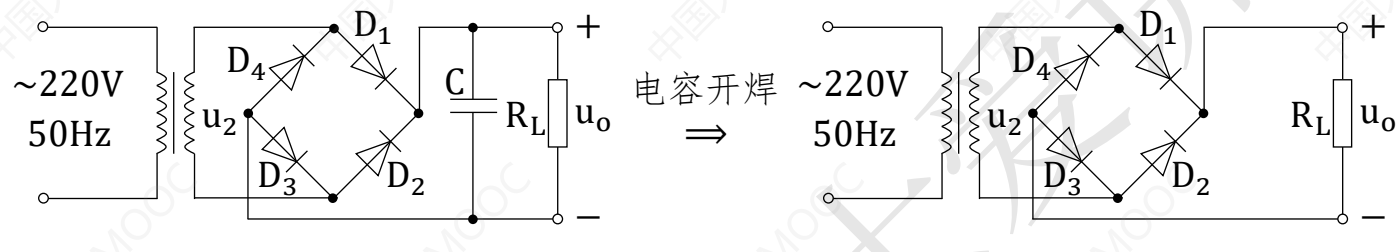
电容耐压值 $U_C = \sqrt{2}U_2 = \sqrt{2} \times 20V = 28.28V$

二极管最大反向电压 $U_{Rmax} = \sqrt{2}U_2 = \sqrt{2} \times 20V = 28.28V$

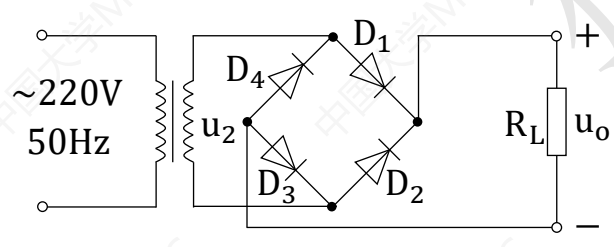
(2) 若电容开焊，且考虑电压波动，求二极管最大反向电压

① 判断电路类型





② 将变压器中，靠近 $\mathbf{u_o}$ 侧的电压记作 $\mathbf{U_2}$

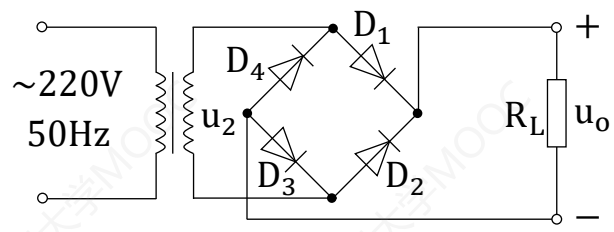


(2) $U_2 = u_2 = 20V$

③ 根据电路的类型套公式求参数

桥式整流电路： 输出电压平均值 $\mathbf{U_O = 0.9U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$
电容滤波电路： 输出电压平均值 $\mathbf{U_O = 1.2U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$、电容耐压值 $\mathbf{U_C = 1.1\sqrt{2}U_2}$
电感滤波电路： 输出电压平均值 $\mathbf{U_O = 0.9\,U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = \frac{1.1}{2} I_O}$
半波整流电路： 输出电压平均值 $\mathbf{U_O = 0.45U_2}$、输出电流平均值 $\mathbf{I_O = \frac{U_O}{R_L}}$ 二极管最大平均电流 $\mathbf{I_D = 1.1I_O}$
四种类型共用：二极管最大反向电压 $\mathbf{U_{Rmax} = 1.1\sqrt{2}U_2}$

【注意：若题干没提电压波动，则将 1.1 变为 1】



桥式整流电路

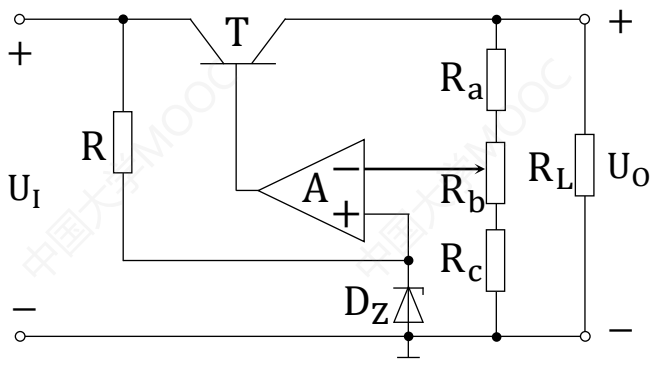
(2) $U_2 = u_2 = 20V$

二极管最大反向电压 $U_{Rmax} = 1.1\sqrt{2}U_2 = 1.1 \times \sqrt{2} \times 20V$

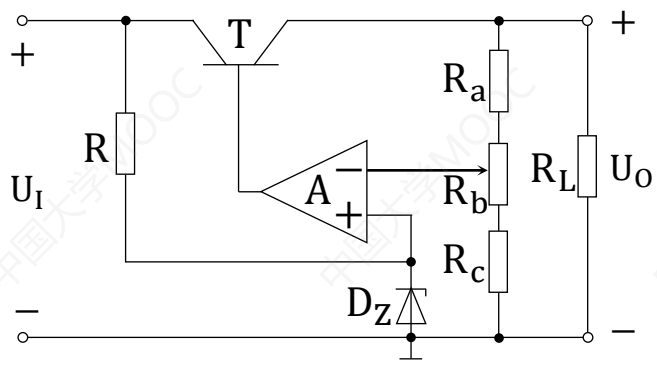
$= 31.11V$

串联型稳压电路

例1. 电路如图所示，已知 $R_a = 200\Omega$，$R_b = 600\Omega$，$R_c = 200\Omega$，稳压管稳定电压 $U_Z = 4V$，请判断输出电压的取值范围



①将串联的三个电阻，从上往下依次记作 $\mathbf{R_1}$、$\mathbf{R_2}$、$\mathbf{R_3}$



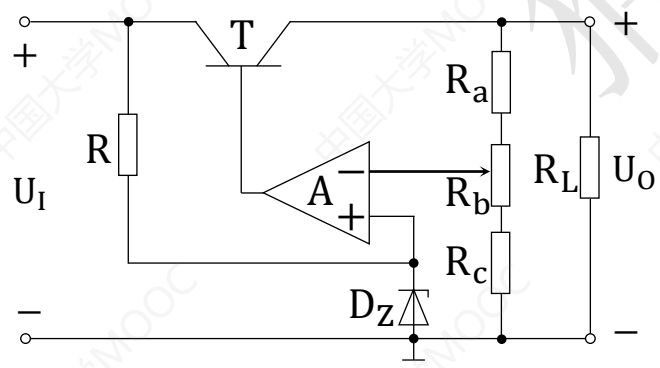
$R_1 = R_a = 200\Omega$

$R_2 = R_b = 600\Omega$

$R_3 = R_c = 200\Omega$

② 输出电压最小值 $\mathbf{U_{Omin} = \frac{R_1+R_2+R_3}{R_2+R_3} \cdot U_Z}$

输出电压最大值 $\mathbf{U_{Omax} = \frac{R_1+R_2+R_3}{R_3} \cdot U_Z}$



$R_1 = R_a = 200\Omega$

$R_2 = R_b = 600\Omega$

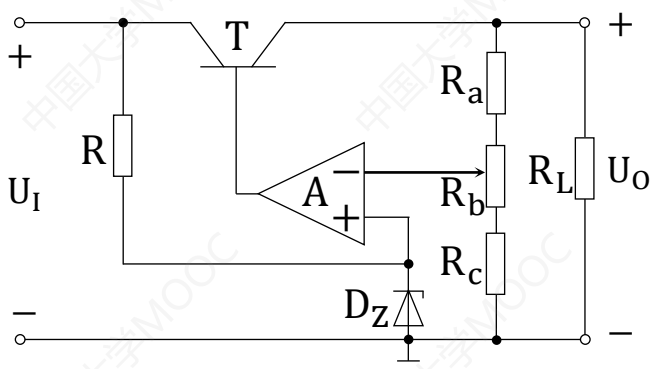
$R_3 = R_c = 200\Omega$

$$U_{Omin} = \frac{R_1+R_2+R_3}{R_2+R_3} \cdot U_Z = \frac{200\Omega + 600\Omega + 200\Omega}{600\Omega + 200\Omega} \cdot 4V = \frac{1000\Omega}{800\Omega} \cdot 4V = 5V$$

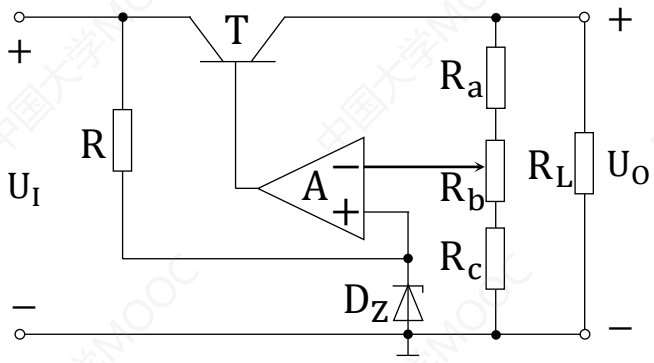
$$U_{Omax} = \frac{R_1+R_2+R_3}{R_3} \cdot U_Z = \frac{200\Omega + 600\Omega + 200\Omega}{200\Omega} \cdot 4V = \frac{1000\Omega}{200\Omega} \cdot 4V = 20V$$

输出电压的取值范围为5V~20V

例2. 电路如图所示，已知输出电压的调节范围为5V~20V，$R_a=200\Omega$ $R_c=200\Omega$，求稳压管的稳定电压 U_Z 和电阻 R_b 的值



①将串联的三个电阻，从上往下依次记作 $\mathbf{R_1}$、$\mathbf{R_2}$、$\mathbf{R_3}$



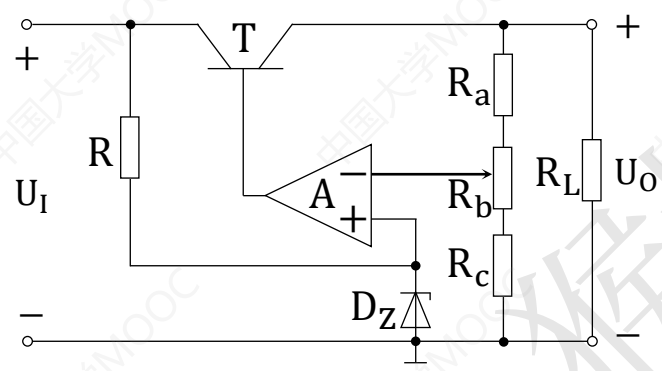
$R_1 = R_a = 200\Omega$

$R_2 = R_b$

$R_3 = R_c = 200\Omega$

② 输出电压最小值 $\mathbf{U_{Omin}=\frac{R_1+R_2+R_3}{R_2+R_3}\cdot U_Z}$

输出电压最大值 $\mathbf{U_{Omax}=\frac{R_1+R_2+R_3}{R_3}\cdot U_Z}$



$R_1 = R_a = 200\Omega$

$R_2 = R_b$

$R_3 = R_c = 200\Omega$

$$U_{Omin}=\frac{R_1+R_2+R_3}{R_2+R_3}\cdot U_Z=\frac{200\Omega+R_b+200\Omega}{R_b+200\Omega}\cdot U_Z=\frac{R_b+400\Omega}{R_b+200\Omega}\cdot U_Z \implies 5V=\frac{R_b+400\Omega}{R_b+200\Omega}\cdot U_Z$$

$$U_{Omax}=\frac{R_1+R_b+R_3}{R_3}\cdot U_Z=\frac{200\Omega+R_b+200\Omega}{200\Omega}\cdot U_Z=\frac{R_b+400\Omega}{200\Omega}\cdot U_Z \implies 20V=\frac{R_b+400\Omega}{200\Omega}\cdot U_Z$$

$$\implies \begin{cases} 5V=\frac{R_b+400\Omega}{R_b+200\Omega}\cdot U_Z & ① \\ 20V=\frac{R_b+400\Omega}{200\Omega}\cdot U_Z & ② \end{cases} \xrightarrow{\text{变一下①}} \begin{cases} U_Z=5V\cdot\frac{R_b+200\Omega}{R_b+400\Omega} & ③ \\ 20V=\frac{R_b+400\Omega}{200\Omega}\cdot U_Z & ② \end{cases} \xrightarrow{\text{将}U_Z=5V\cdot\frac{R_b+200\Omega}{R_b+400\Omega}\text{代入②}} 20V=\frac{R_b+400\Omega}{200\Omega}\cdot 5V\cdot\frac{R_b+200\Omega}{R_b+400\Omega}$$

$$\xleftarrow{\text{左右同除以5V}} \frac{20V}{5V}=\frac{R_b+400\Omega}{200\Omega}\cdot\frac{R_b+200\Omega}{R_b+400\Omega} \longleftarrow 4=\frac{R_b+200\Omega}{200\Omega} \longleftarrow R_b=600\Omega \xleftarrow{\text{将}R_b=600\Omega\text{代入②}} 20V=\frac{600\Omega+400\Omega}{200\Omega}\cdot U_Z \longleftarrow U_Z=4V$$