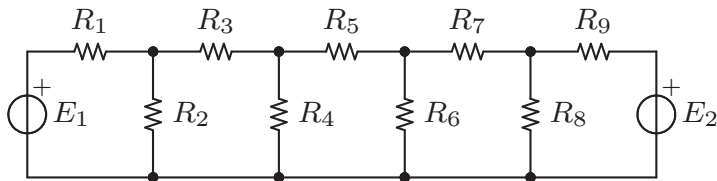


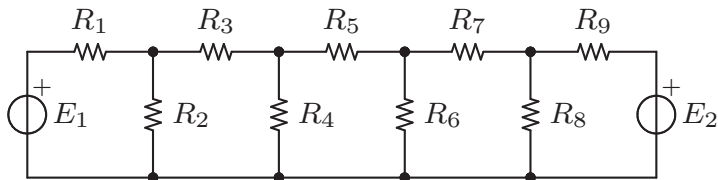
10. Control Theory

Example 10.1.1 (p. 219)

Find the current in the branch with resistance R_5 in the following circuit.



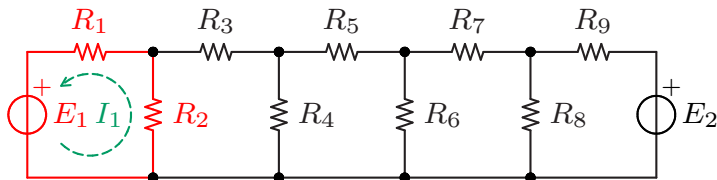
Electrical circuit



Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

Electrical circuit

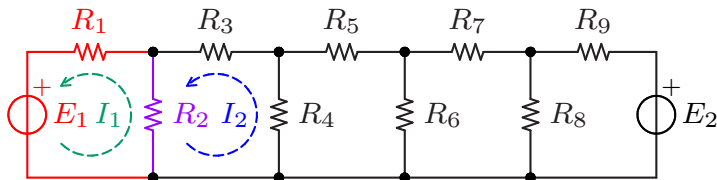


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{11} = R_1 + R_2$,

Electrical circuit

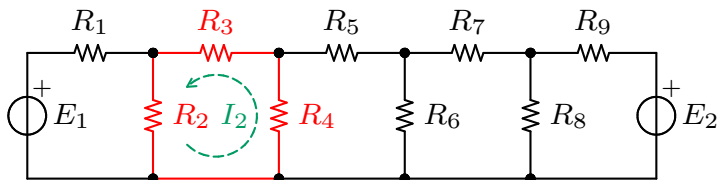


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{12} = R_2$,

Electrical circuit

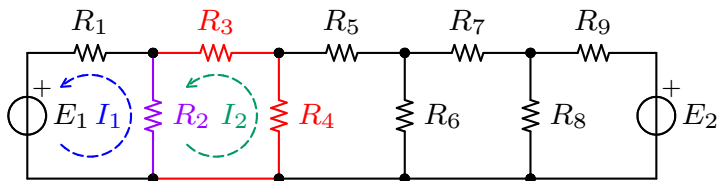


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{22} = R_2 + R_3 + R_4$,

Electrical circuit

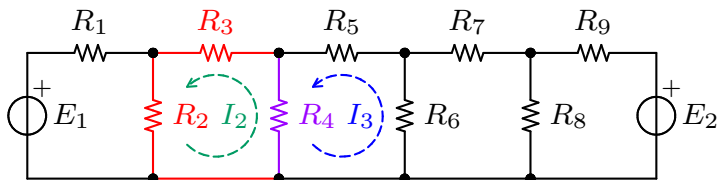


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{21} = R_2$,

Electrical circuit

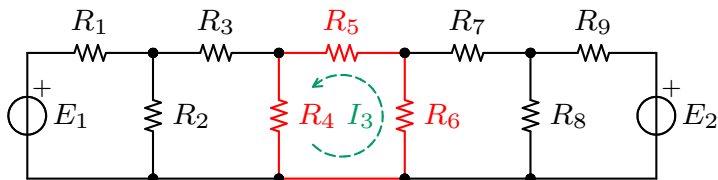


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{23} = R_4$,

Electrical circuit

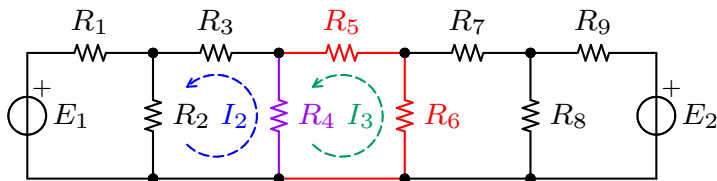


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{33} = R_4 + R_5 + R_6$,

Electrical circuit

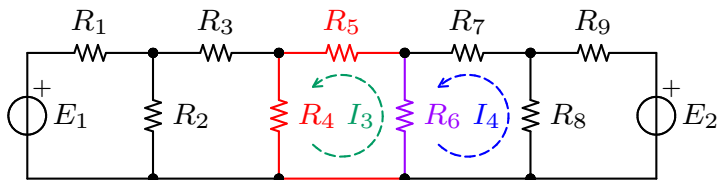


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{32} = R_4$,

Electrical circuit

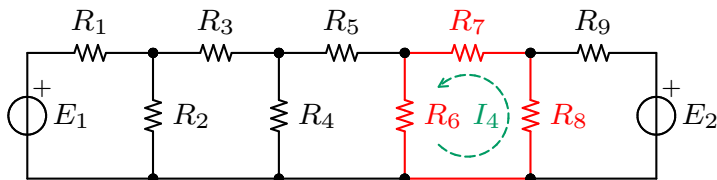


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{34} = R_6$,

Electrical circuit

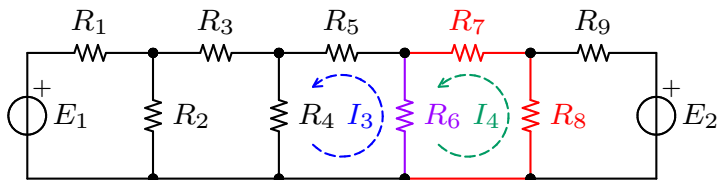


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{44} = R_6 + R_7 + R_8$,

Electrical circuit

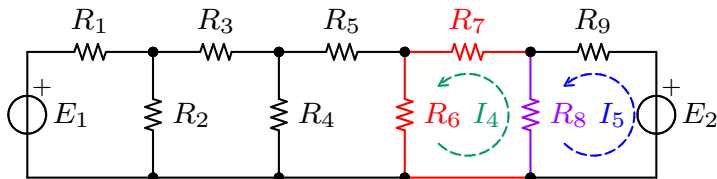


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{43} = R_6$,

Electrical circuit

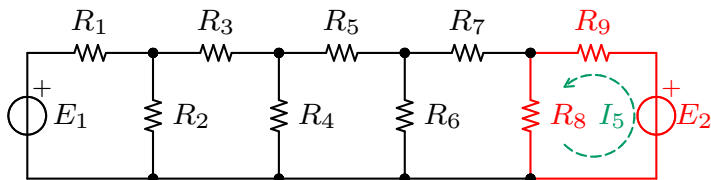


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{45} = R_8$,

Electrical circuit

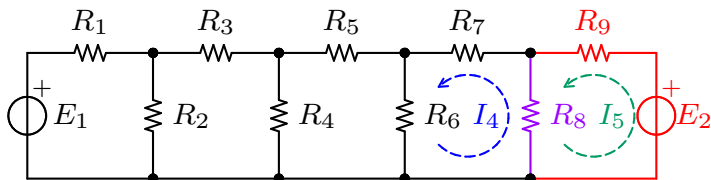


Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{55} = R_8 + R_9$,

Electrical circuit



Loop current equations

$$\begin{aligned}
 R_{11}I_1 - R_{12}I_2 &= -E_1 \\
 -R_{21}I_1 + R_{22}I_2 - R_{23}I_3 &= 0 \\
 -R_{32}I_2 + R_{33}I_3 - R_{34}I_4 &= 0 \\
 -R_{43}I_3 + R_{44}I_4 - R_{45}I_5 &= 0 \\
 -R_{54}I_4 + R_{55}I_5 &= E_2
 \end{aligned}$$

where $R_{54} = R_8$.

Loop current equations

$$R_{11}I_1 - R_{12}I_2 = -E_1$$

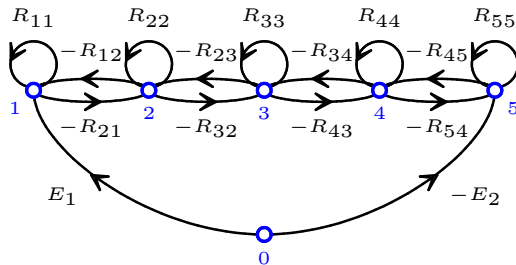
$$-R_{21}I_1 + R_{22}I_2 - R_{23}I_3 = 0$$

$$-R_{32}I_2 + R_{33}I_3 - R_{34}I_4 = 0$$

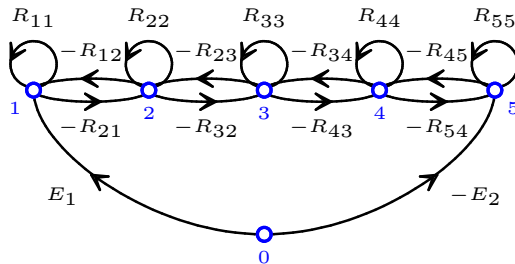
$$-R_{43}I_3 + R_{44}I_4 - R_{45}I_5 = 0$$

$$-R_{54}I_4 + R_{55}I_5 = E_2$$

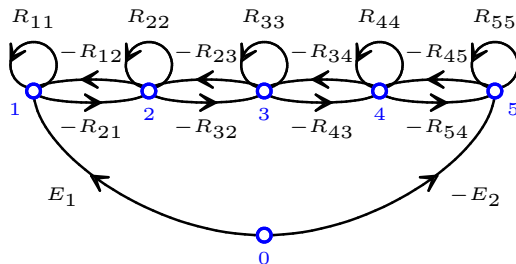
The Coates digraph



The Coates digraph



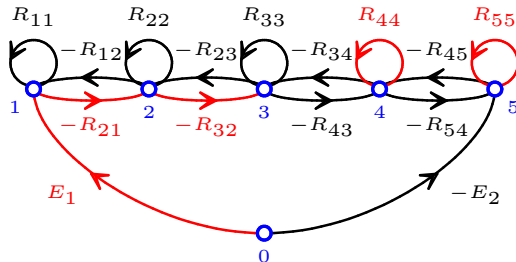
The current I_3 through R_5 corresponds to vertex **3** and can be obtained by using Coates formula.



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

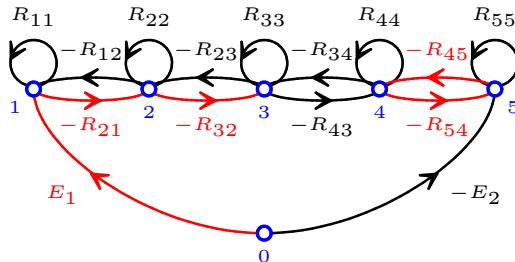
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

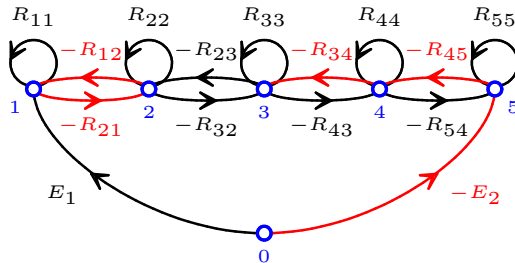
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

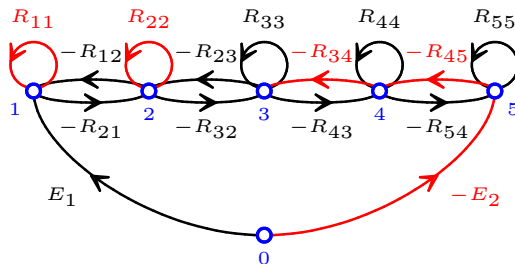
$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} +$$

$$E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} +$$

$$R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} +$$

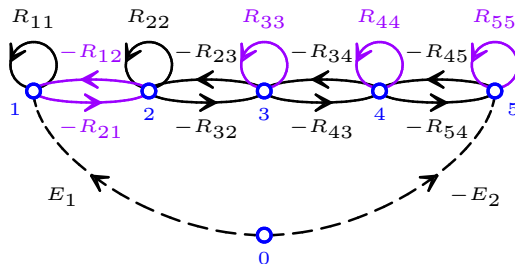
$$R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

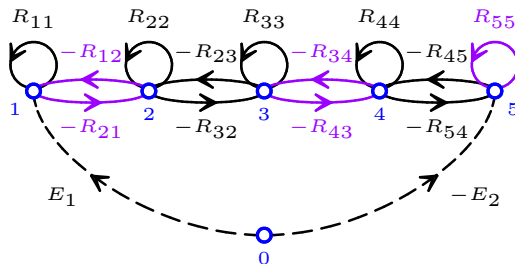
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

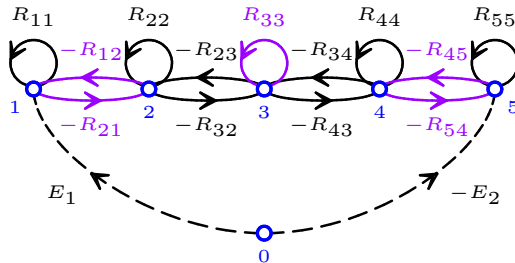
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

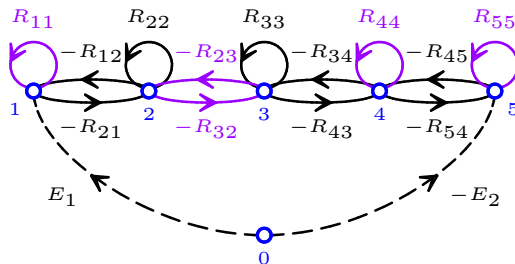
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

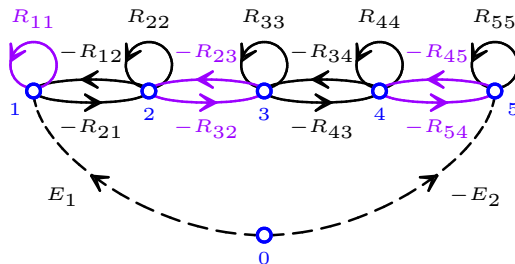
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

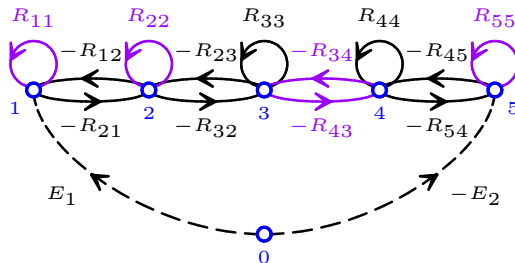
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

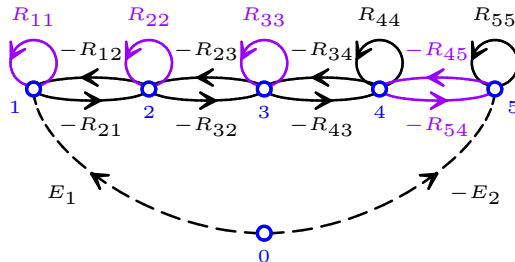
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

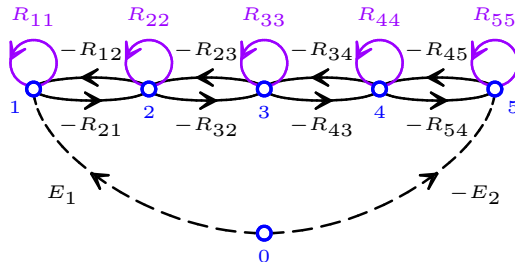
$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



$$I_3 = \frac{N}{D}$$

$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$



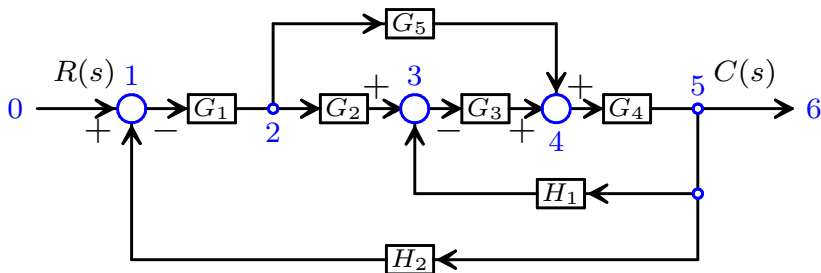
$$I_3 = \frac{N}{D}$$

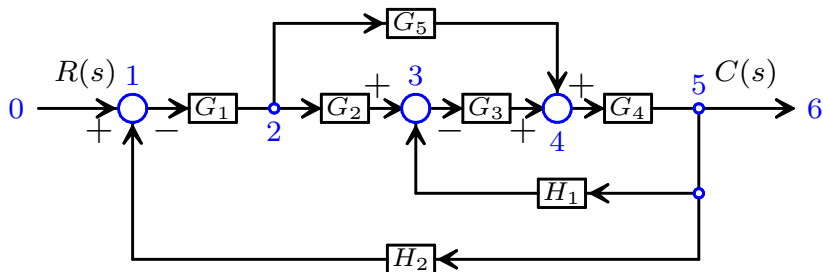
$$N = E_1 R_{21} R_{32} R_{44} R_{55} - E_1 R_{21} R_{32} R_{45} R_{54} + \\ E_2 R_{45} R_{34} R_{12} R_{21} - E_2 R_{45} R_{34} R_{11} R_{22}$$

$$D = R_{12} R_{21} R_{33} R_{44} R_{55} - R_{12} R_{21} R_{34} R_{43} R_{55} + R_{12} R_{21} R_{33} R_{45} R_{54} + \\ R_{11} R_{23} R_{32} R_{44} R_{55} - R_{11} R_{23} R_{32} R_{45} R_{54} + R_{11} R_{22} R_{34} R_{43} R_{55} + \\ R_{11} R_{22} R_{33} R_{45} R_{54} - R_{11} R_{22} R_{33} R_{44} R_{55}$$

Example 10.1.3 (p. 223)

Find the transfer function for the following system





Block diagram

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

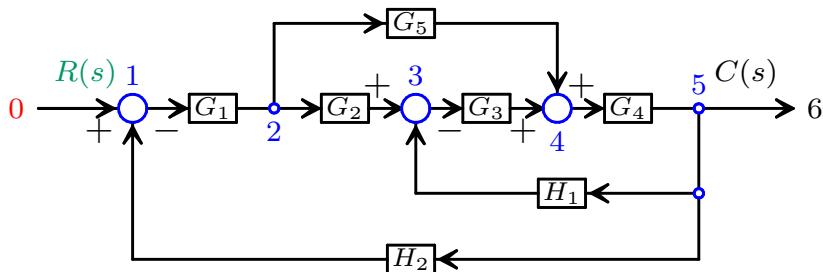
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

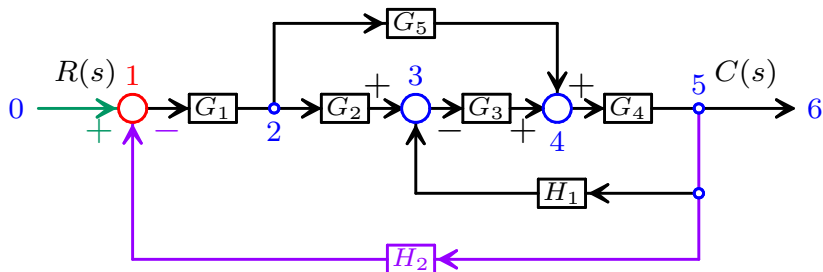
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

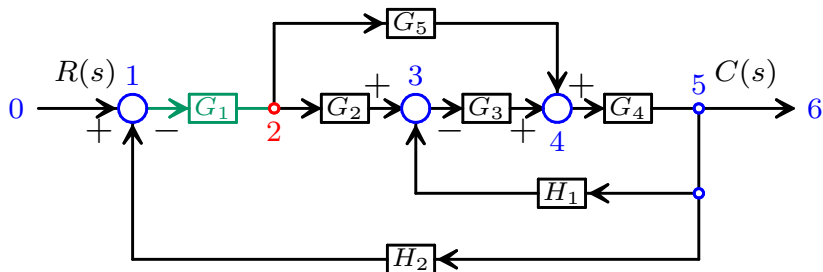
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$\textcolor{red}{x}_2 = \textcolor{teal}{G}_1 x_1$$

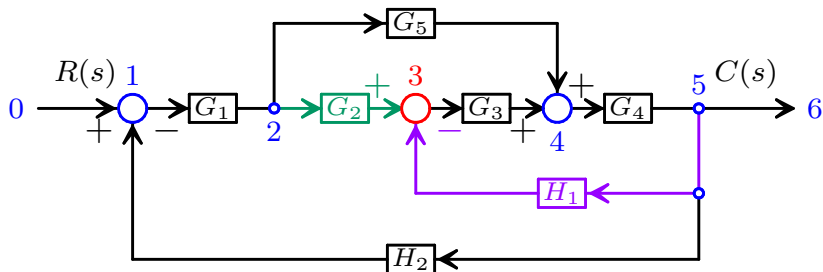
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

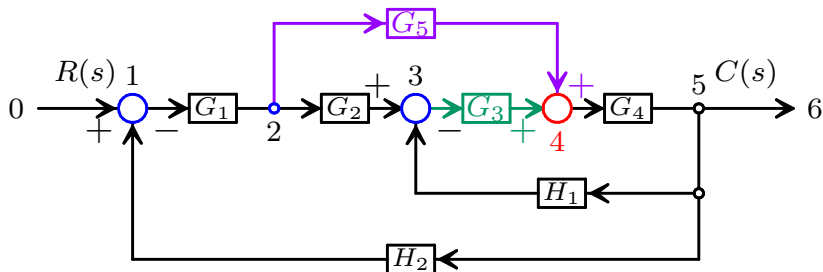
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

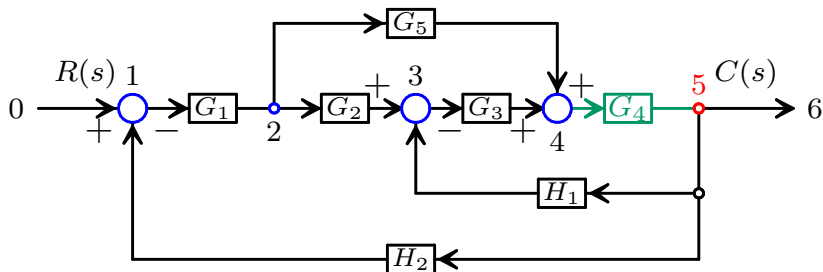
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

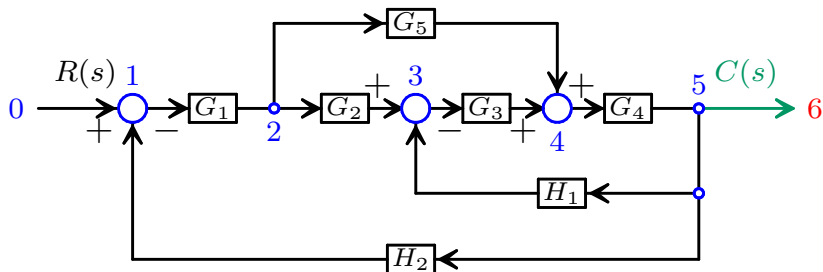
$$x_4 = G_3 x_3 + G_5 x_2$$

$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$\textcolor{red}{x}_5 = \textcolor{teal}{G}_4 x_4$$



Equations

$$x_0 = R(s)$$

$$x_2 = G_1 x_1$$

$$x_4 = G_3 x_3 + G_5 x_2$$

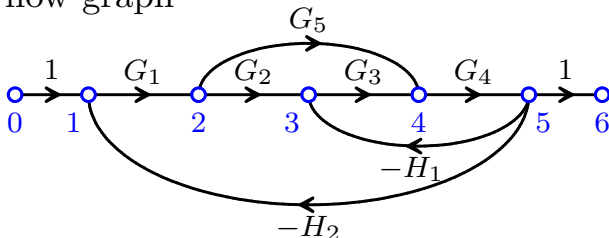
$$x_6 = C(s) = x_5$$

$$x_1 = x_0 - H_2 x_5$$

$$x_3 = G_2 x_2 - H_1 x_5$$

$$x_5 = G_4 x_4$$

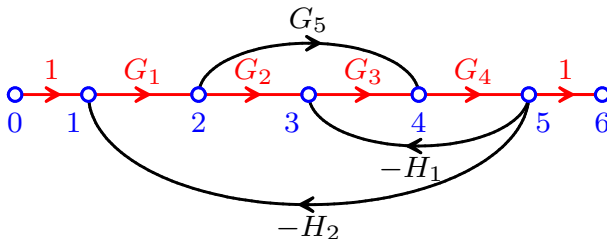
Signal flow graph



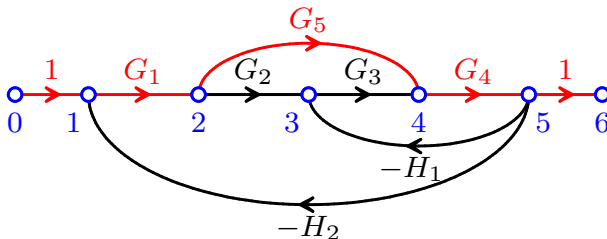
Mason's formula

S.J.Mason, 1953

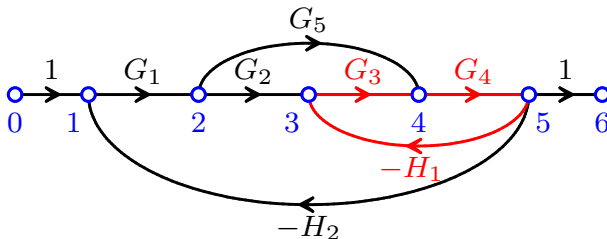
$$\frac{C(s)}{R(s)} = \frac{G_1 G_2 G_3 G_4 + G_1 G_5 G_4}{1 + G_3 G_4 H_1 + G_1 G_2 G_3 G_4 H_2 + G_1 G_5 G_4 H_2}$$



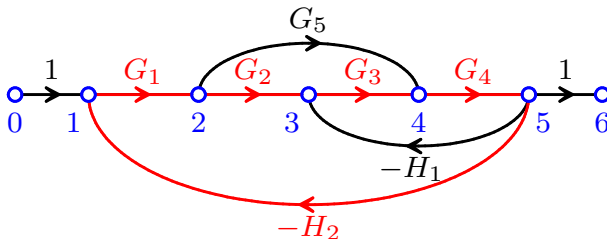
$$\frac{C(s)}{R(s)} = \frac{1G_1G_2G_3G_41 + 1G_1G_5G_41}{1 + G_3G_4H_1 + G_1G_2G_3G_4H_2 + G_1G_5G_4H_2}$$



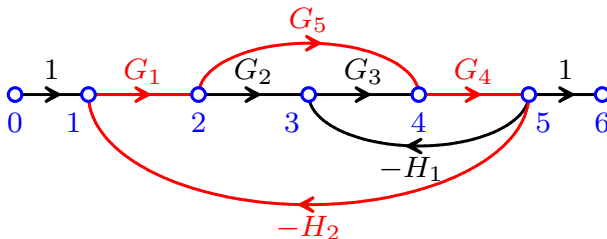
$$\frac{C(s)}{R(s)} = \frac{1G_1G_2G_3G_41 + \textcolor{red}{1}G_1\textcolor{red}{G_5}G_41}{1 + G_3G_4H_1 + G_1G_2G_3G_4H_2 + G_1G_5G_4H_2}$$



$$\frac{C(s)}{R(s)} = \frac{1G_1G_2G_3G_41 + 1G_1G_5G_41}{1 + \textcolor{red}{G_3G_4H_1} + G_1G_2G_3G_4H_2 + G_1G_5G_4H_2}$$



$$\frac{C(s)}{R(s)} = \frac{1G_1G_2G_3G_41 + 1G_1G_5G_41}{1 + G_3G_4H_1 + \textcolor{red}{G_1G_2G_3G_4H_2} + G_1G_5G_4H_2}$$



$$\frac{C(s)}{R(s)} = \frac{1G_1G_2G_3G_41 + 1G_1G_5G_41}{1 + G_3G_4H_1 + G_1G_2G_3G_4H_2 + \textcolor{red}{G_1G_5G_4H_2}}$$