06.2 trans.firsto First-order systems in transient response

1 First order systems have input-output differential equations of the form

$$\tau \frac{dy}{dt} + y = b_1 \frac{du}{dt} + b_0 u \qquad (1)$$

with $\tau \in \mathbb{R}$ called the **time constant** of the system. Systems with a single energy storage element—such as those with electrical or thermal capacitance—can be modeled as first-order.

2 The characteristic equation yields a single root $\lambda = -1/\tau$, so the **homogeneous solution** y_h, for constant $\kappa \in \mathbb{R}$, is

Free response

3 The **free response** y_{fr} of a system is its response to initial conditions and no forcing ($f(t) = 0$). This is useful for two reasons:

1. perturbations of the system from equilibrium result in free response and
2. from superposition, the free response can be added to a forced response to find the specific response: $y(t) = y_{fr}(t) + y_{fo}(t)$. This allows us to use tables of solutions like Table firsto.1 to construct solutions for systems with nonzero initial conditions with forcing.

4 The free response is found by applying initial conditions to the homogeneous solution. With initial condition $y(0)$, the free response is

$$y_{fr}(t) = y(0)\, e^{-t/\tau}, \qquad (2)$$

which begins at $y(0)$ and decays exponentially to zero.

Step response

5 In what follows, we develop **forced response** y_{fo} solutions, which are the *specific solution* responses of systems to given inputs and **zero initial conditions**: all initial conditions set to zero.
6 If we consider the common situation that $b_1 = 0$ and $u(t) = Ku_s(t)$ for some $K \in \mathbb{R}$, the solution to Equation 1 is

The non-steady term is simply a constant scaling of a decaying exponential.
7 A plot of the step response is shown in Figure firsto.1. As with the free response, within 5τ the transient response is less than 1% of the difference between $y(0)$ and steady-state.

Impulse and ramp responses

8 The response to all three singularity inputs are included in Table firsto.1. These can be combined with the free response of Equation 2 using superposition. Results could be described as **bitchin'**.

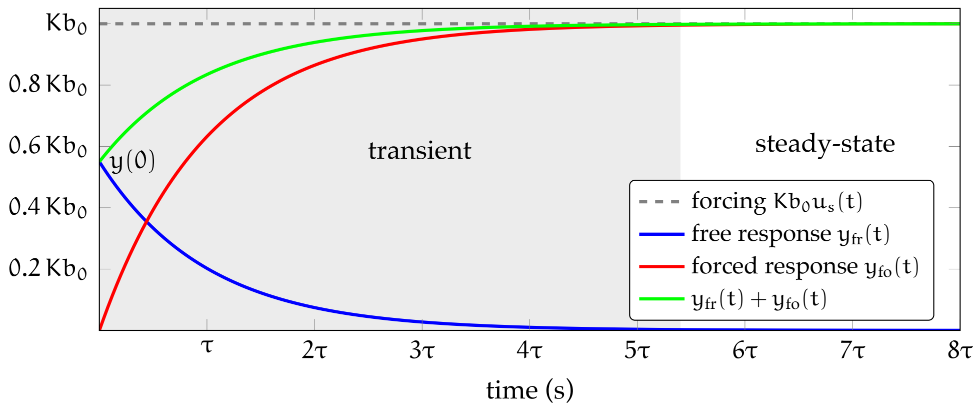

Figure firsto.1: free and forced responses and their sum for a first order system with input $u(t) = Ku_s(t)$, initial condition $y(0)$, and $b_1 = 0$.

Table firsto.1: first-order system characteristic and total forced responses for singularity inputs. The relevant differential equation is of the standard form $\tau\dot{y} + y = f$.

$u(t)$	characteristic response $f(t) = u(t)$	total forced response y_{fo} for $t \geqslant 0$ $f(t) = b_1\dot{u} + b_0 u$
$\delta(t)$	$\frac{1}{\tau}e^{-t/\tau}$	$\frac{b_1}{\tau}\delta(t) + \left(\frac{b_0}{\tau} - \frac{b_1}{\tau^2}\right)e^{-t/\tau}$
$u_s(t)$	$1 - e^{-t/\tau}$	$b_0 - \left(b_0 - \frac{b_1}{\tau}\right)e^{-t/\tau}$
$u_r(t)$	$t - \tau(1 - e^{-t/\tau})$	$b_0 t + (b_1 - b_0\tau)(1 - e^{-t/\tau})$

Example 06.2 trans.firsto-1

re: RC-circuit response the easy way

Consider a parallel RC-circuit with input current $I_S(t) = 2u_s(t)$ A, initial capacitor voltage $v_C(0) = 3$ V, resistance $R = 1000\ \Omega$, and capacitance $C = 1$ mF. Proceeding with the usual analysis would produce the io differential equation

$$C\frac{dv_C}{dt} + v_C/R = I_S.$$

Use Table firsto.1 to find $v_C(t)$.