General Information

Prof. Antonella Ferrara https://scholar.google.com/citations?user=r5JuMskAAAAJ&hl=en

Course Teaching Material: KIRO UNIPV https://elearning.unipv.it/

- 504462 - PROCESS CONTROL 2025-26 - PROF.SSA FERRARA ANTONELLA

Lecture Time-table: http://www-3.unipv.it/ingserv/orario2526/1sem/insegnamenti/ProCont.html

Exams: https://studentionline.unipv.it/esse3/Home.do https://kirotesting.unipv.it/

Introduction

- Program of the course:

Advanced SISO control schemes:
Pre-filters and parallel compensators, two degrees of freedom control schemes, compensation of measurable disturbances, systems with delays and Smith Predictor, Padé approximation, decoupling in the frequency domain, control of open loop unstable systems.

Advanced MIMO control schemes:
Decoupling based control schemes, decentralized control, relative gain array.

PID controllers:
Features and properties. Rules for the empirical calibration. Wind-up and anti wind-up schemes.

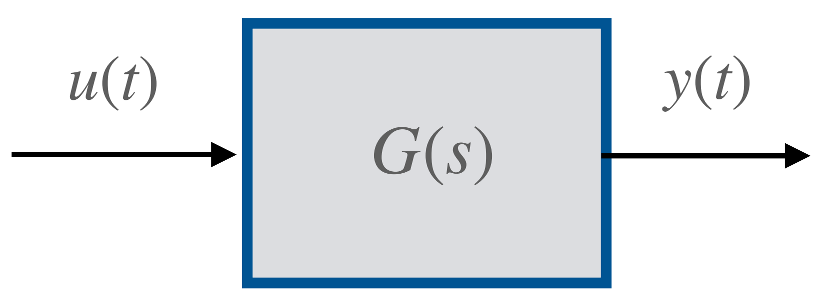
Digital control:
Discrete-time systems. The concept of equilibrium for discrete-time systems. Stability of linear time-invariant discrete-time systems. Jury test. Digital control schemes. Zeta transform and its properties. Transfer functions in the z domain. Sampling and aliasing. Choice of the sampling time. Zero-order-Hold. Discretization of continuous-time controllers. Bilinear transformation, Euler and Tustin methods.

Introduction

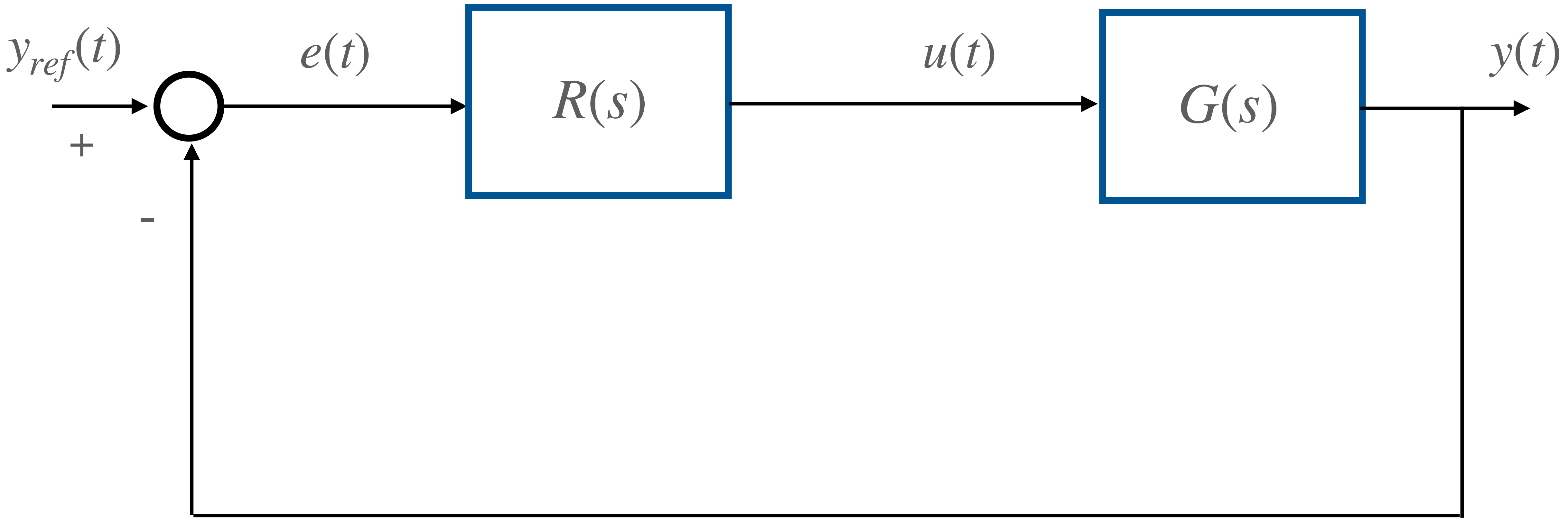
- Some of the figures in these slides, kindly provided by McGraw-Hill, are those of the Textbook:

Design of PID Controllers

Process

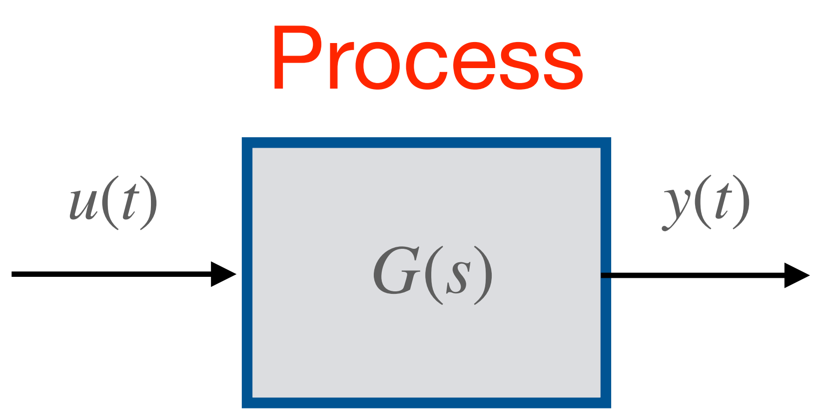


$$u(t) \in \mathbb{R}$$
$$y(t) \in \mathbb{R}$$



Unitary Feedback Control Scheme

Design of PID Controllers



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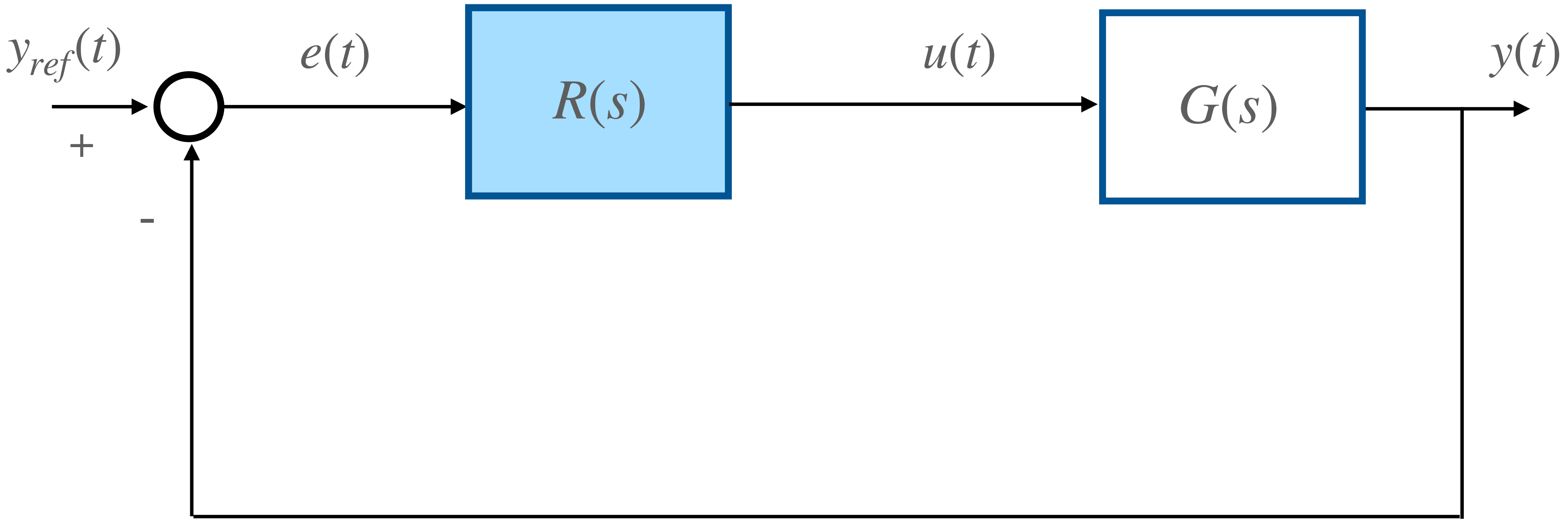
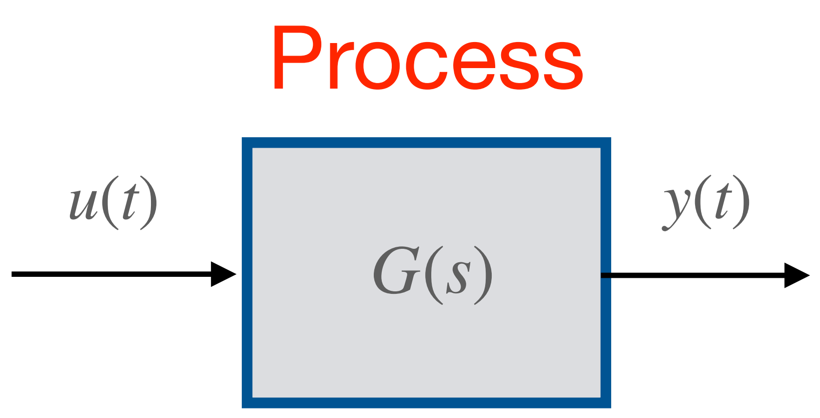


Design of PID Controllers



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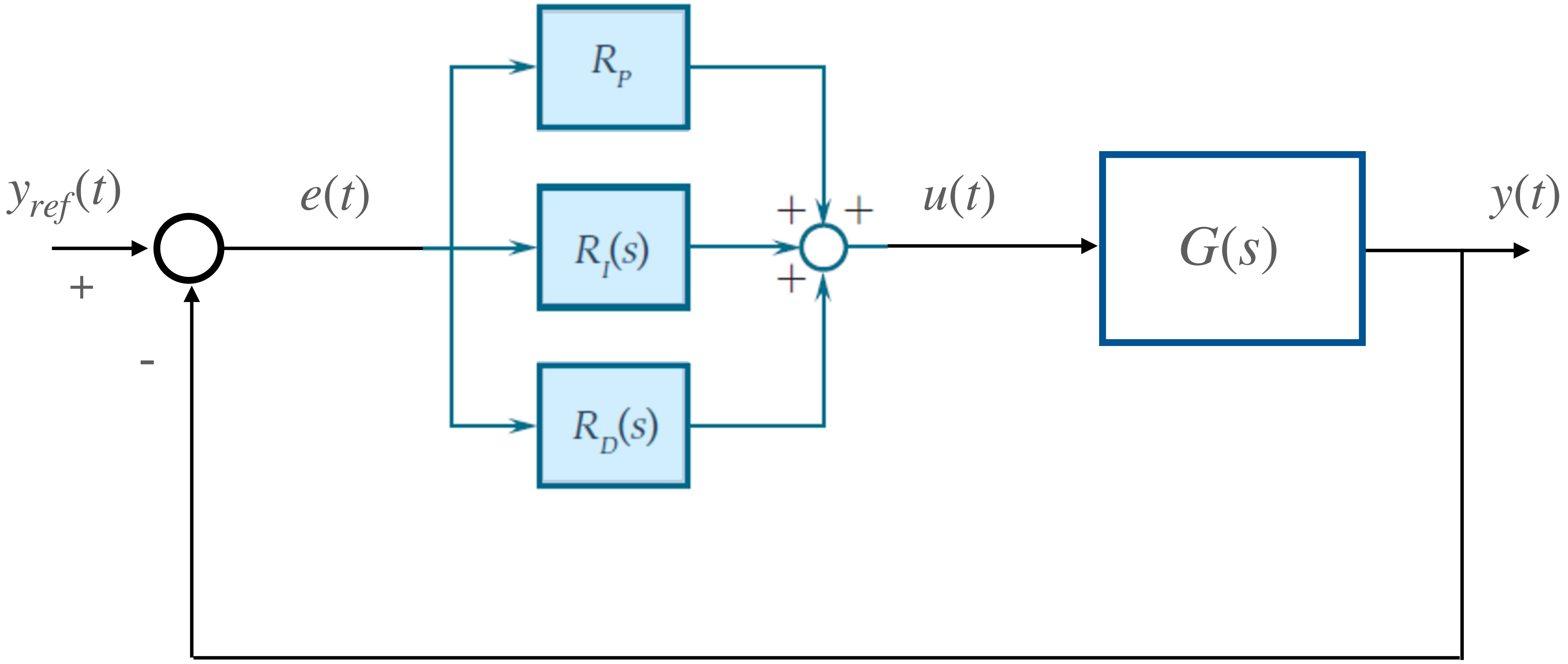

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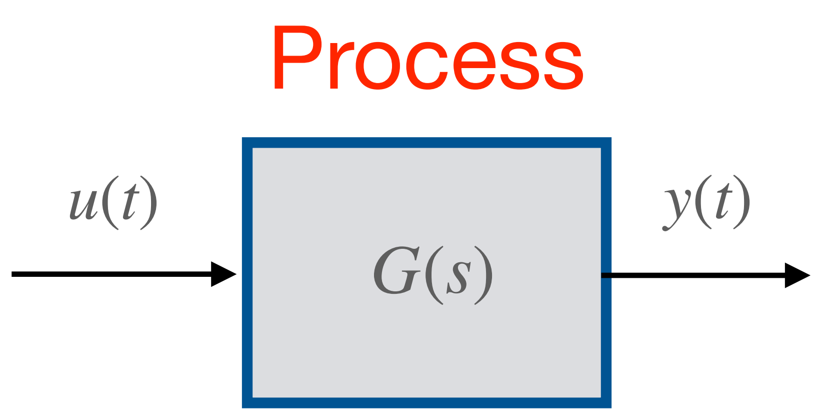

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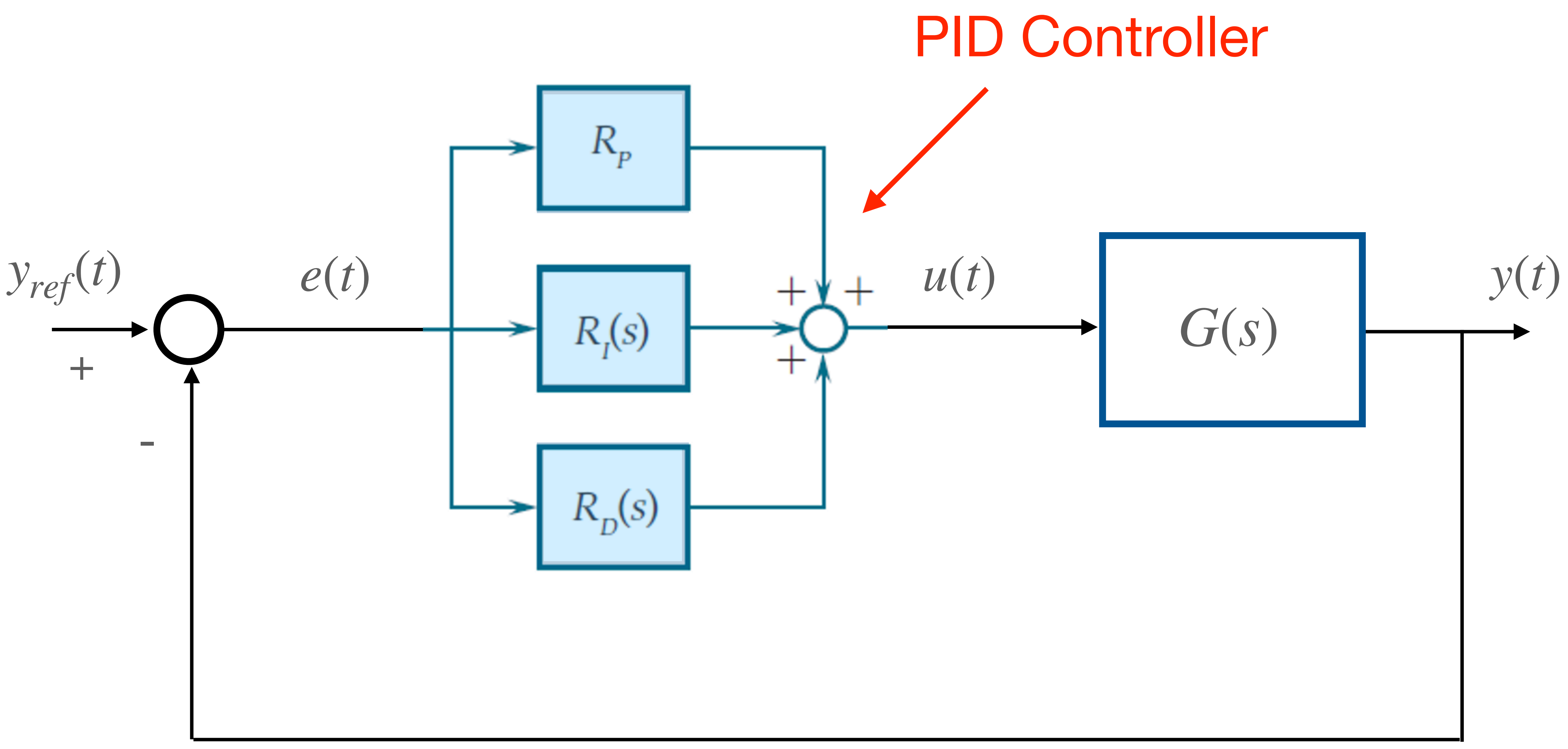

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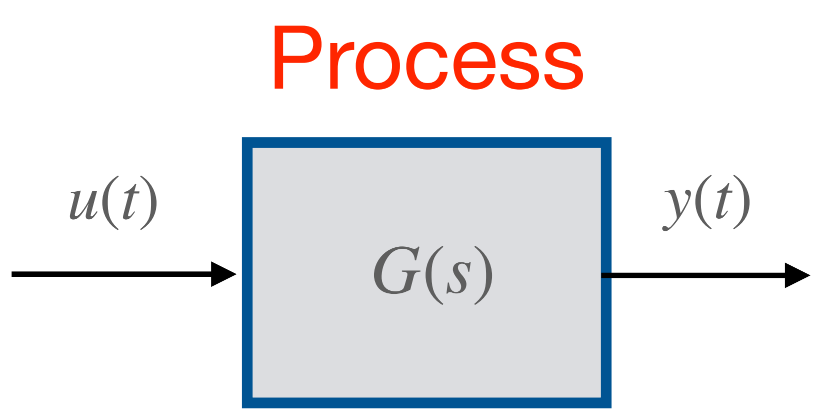

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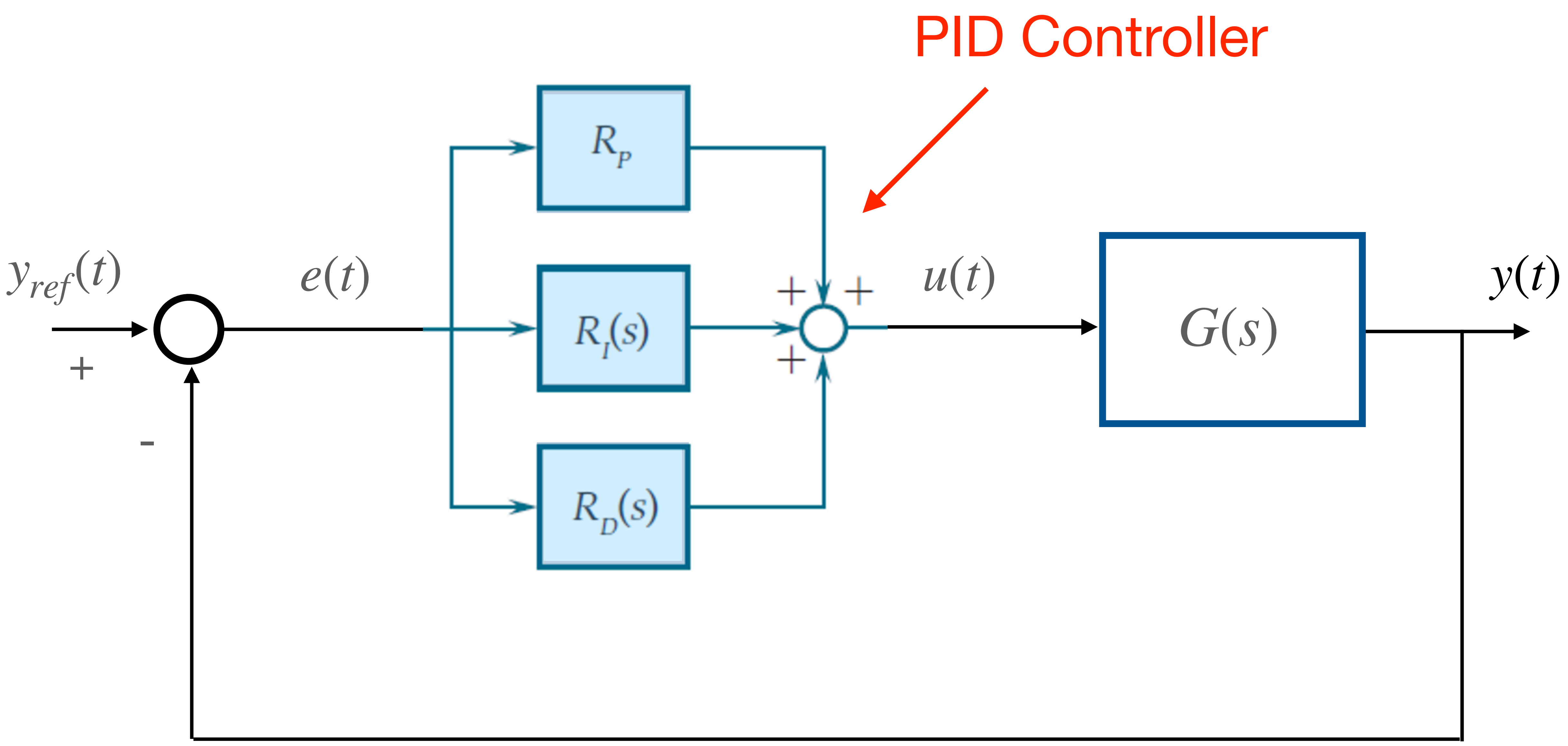
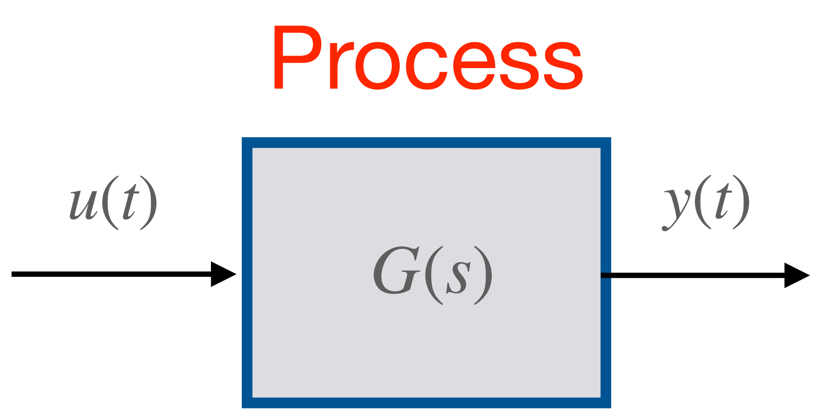


Ideal PID Controller: $u(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau + K_D \frac{de(t)}{dt}$

Design of PID Controllers



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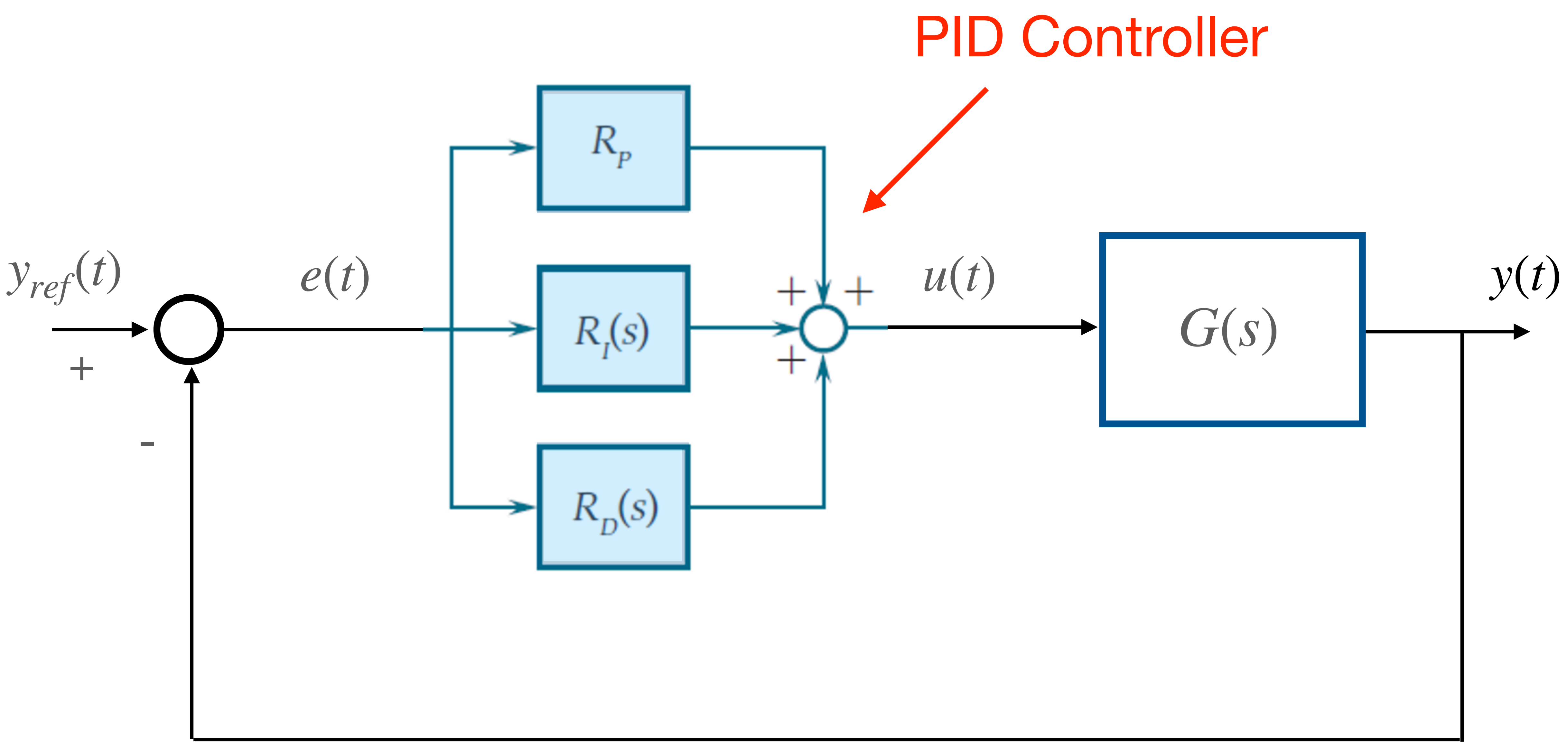

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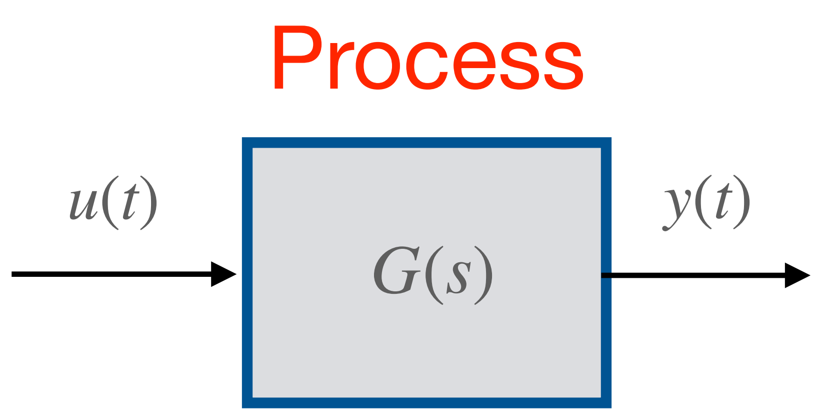
Design of PID Controllers



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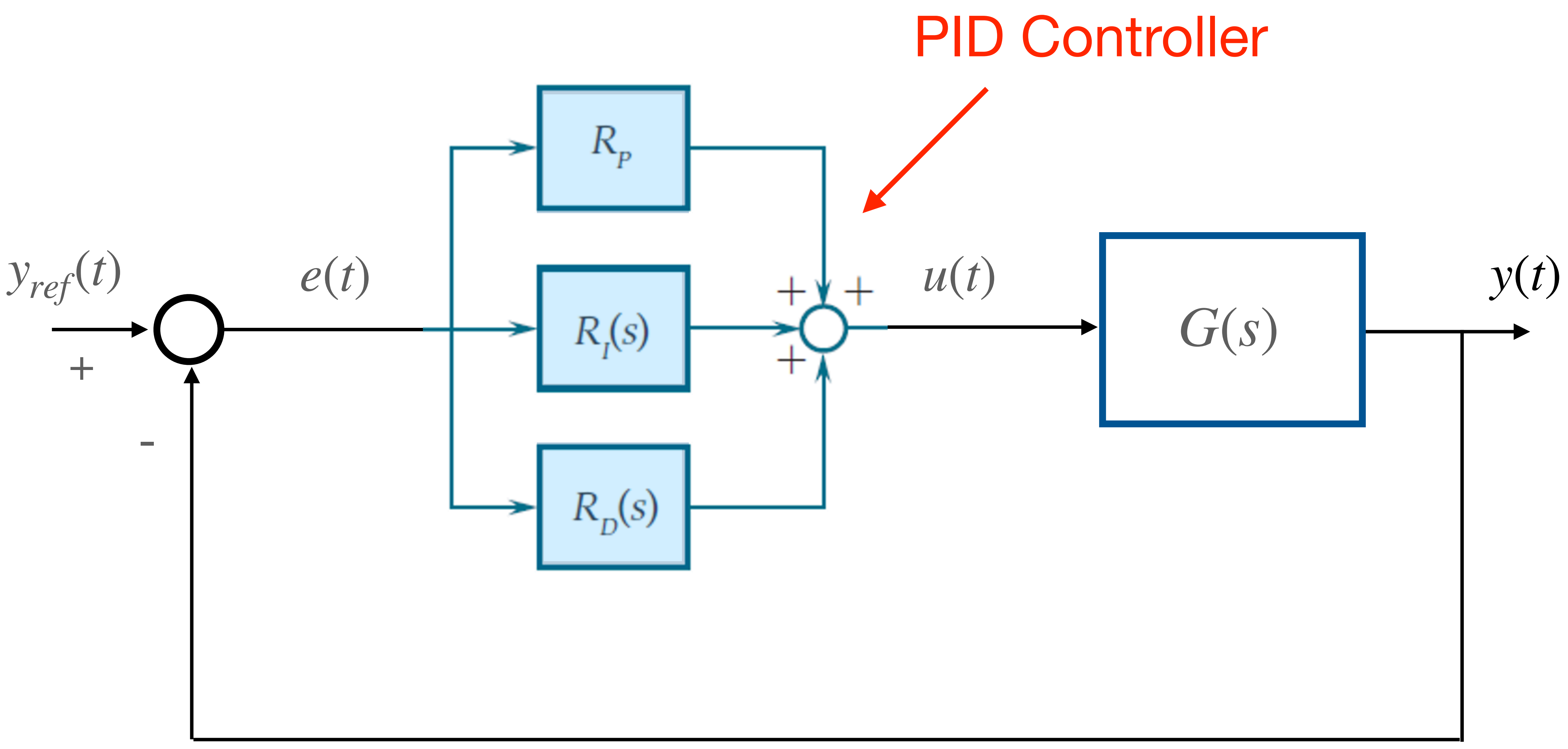

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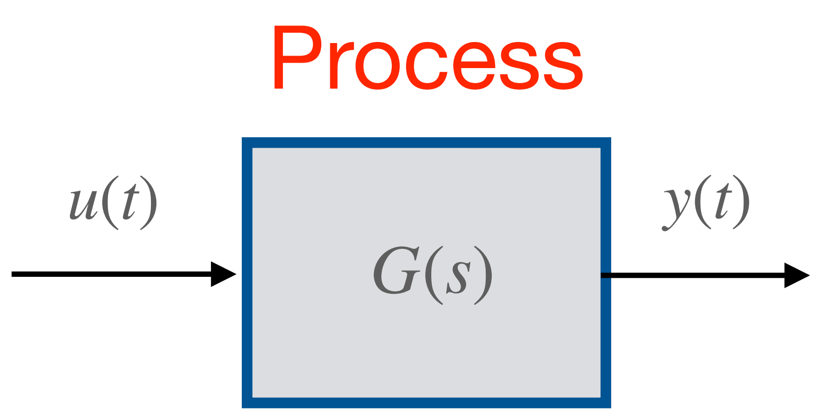
Design of PID Controllers



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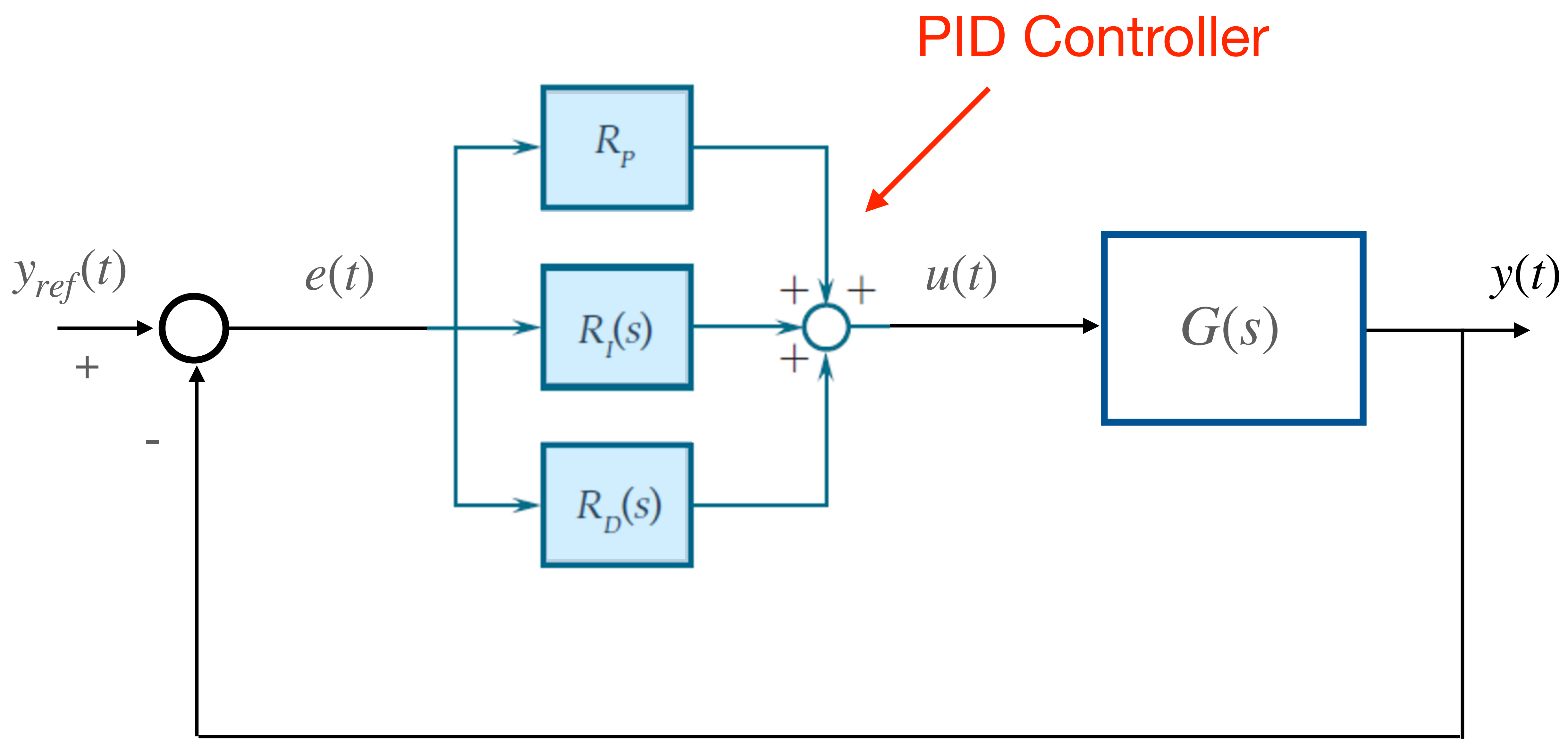

It is not causal

$$R_{PID_{id}}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_P s + K_I}{s}$$

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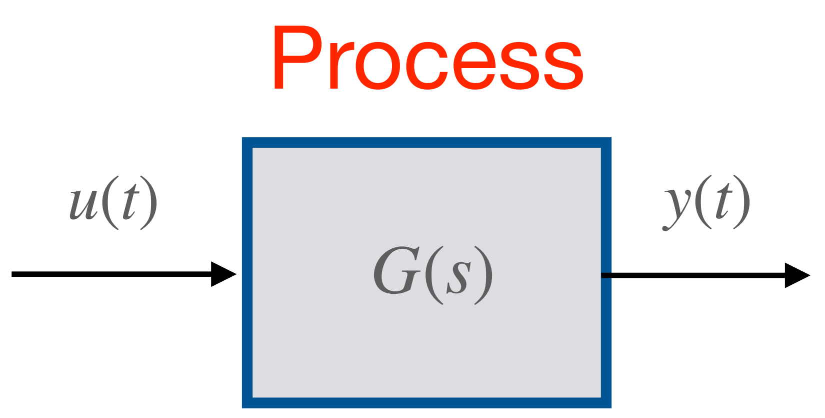
Design of PID Controllers



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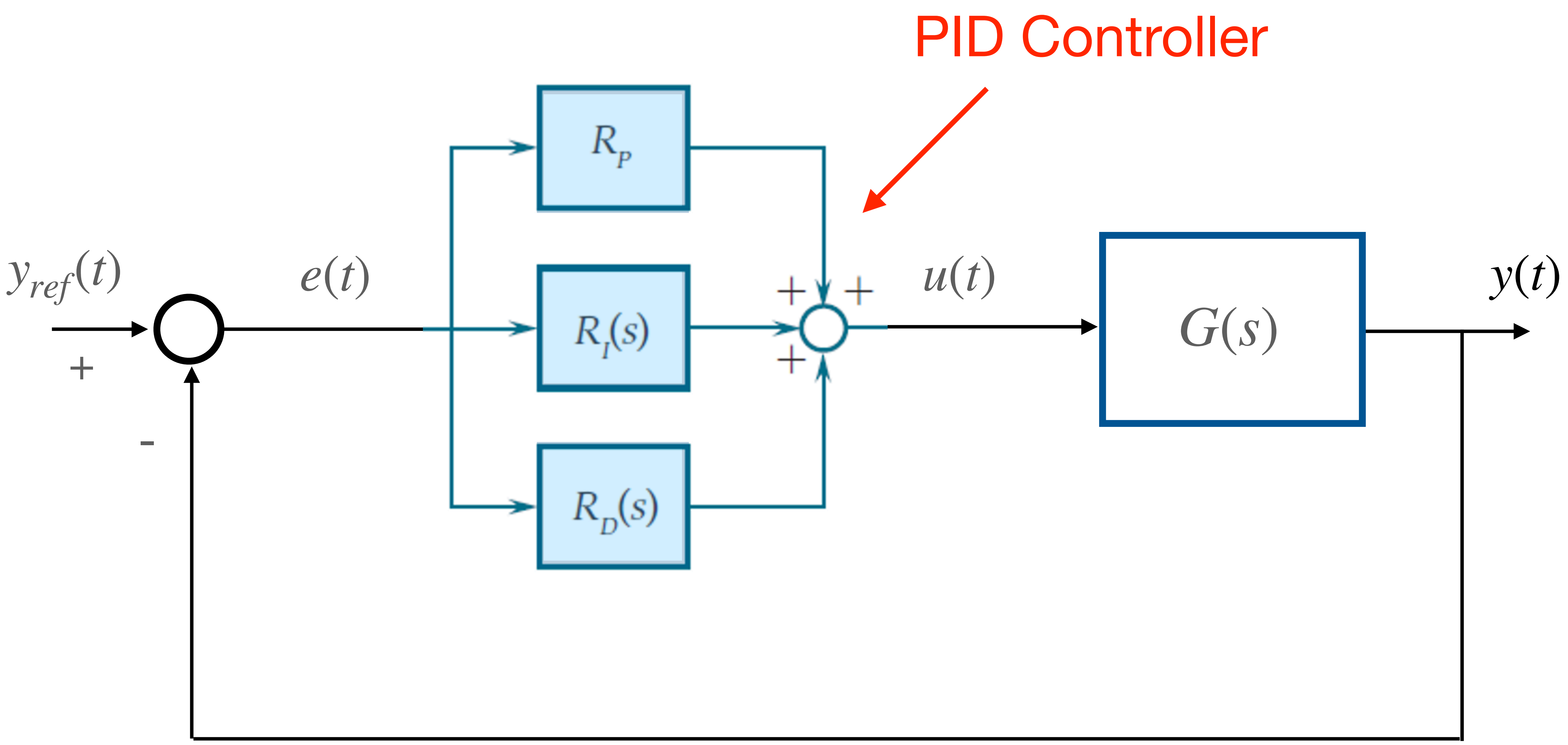

Alternative representation:

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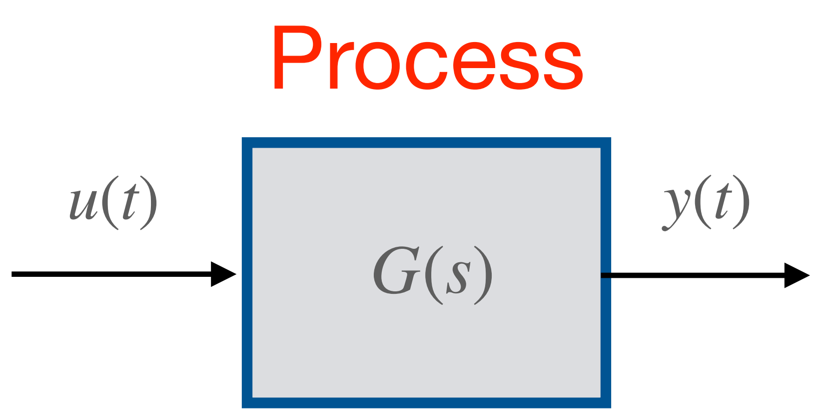
Design of PID Controllers



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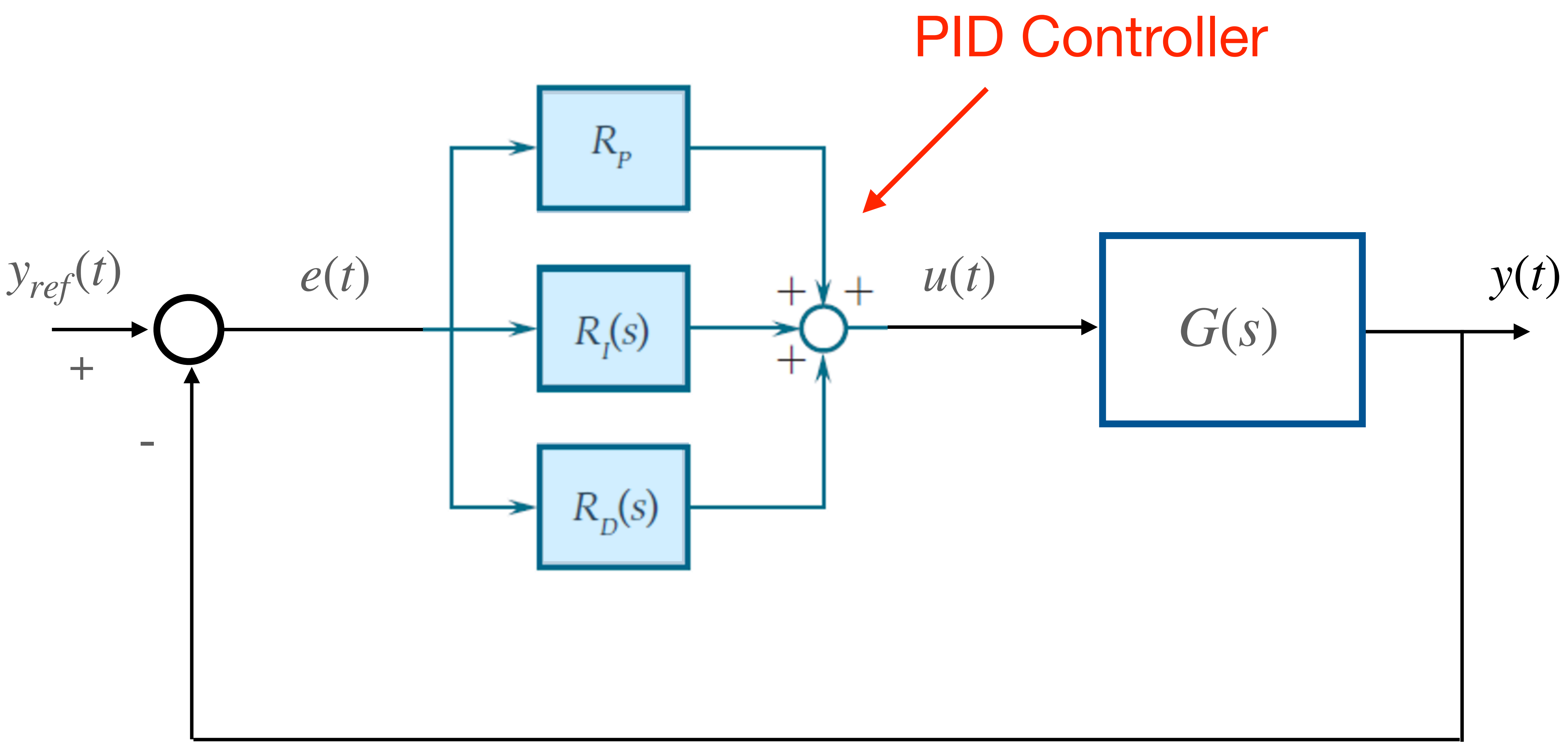

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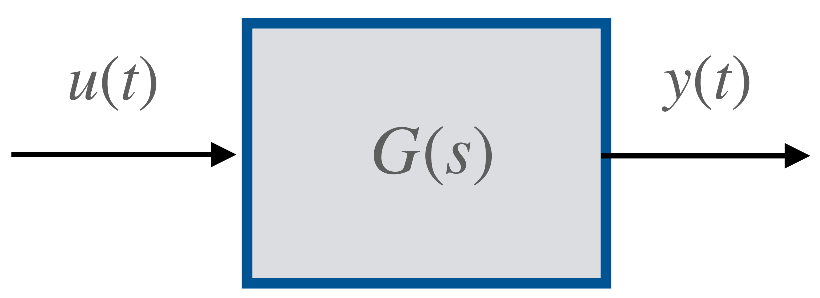
To make it causal

$$R_{PID}(s) = K_P\left(1 + \frac{1}{T_I s} + \frac{T_D s}{1 + \frac{T_D}{N} s}\right)$$

Design of PID Controllers

Process



$u(t) \in \mathbb{R}$

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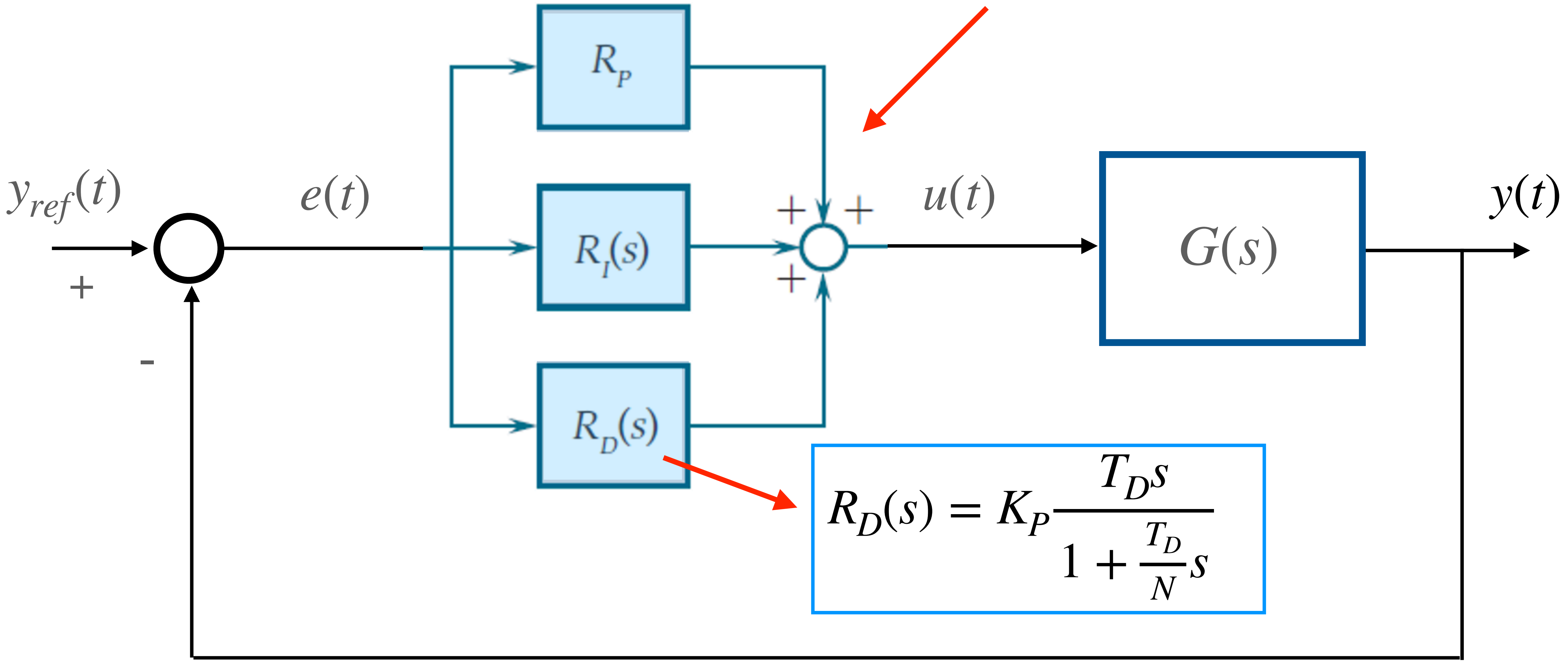
PID Controller: causal version



$$R_D(s) = K_P \frac{T_D s}{1 + \frac{T_D}{N} s}$$

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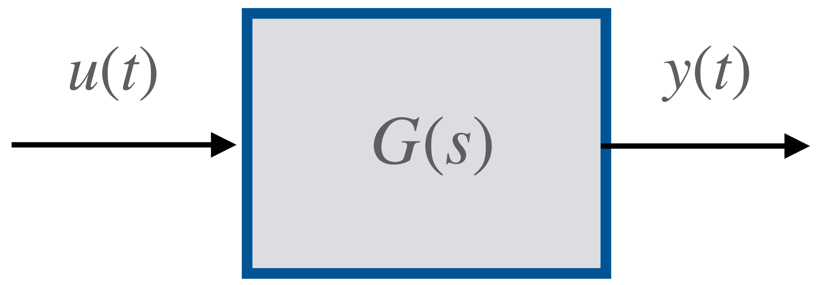
Design of PID Controllers

Process



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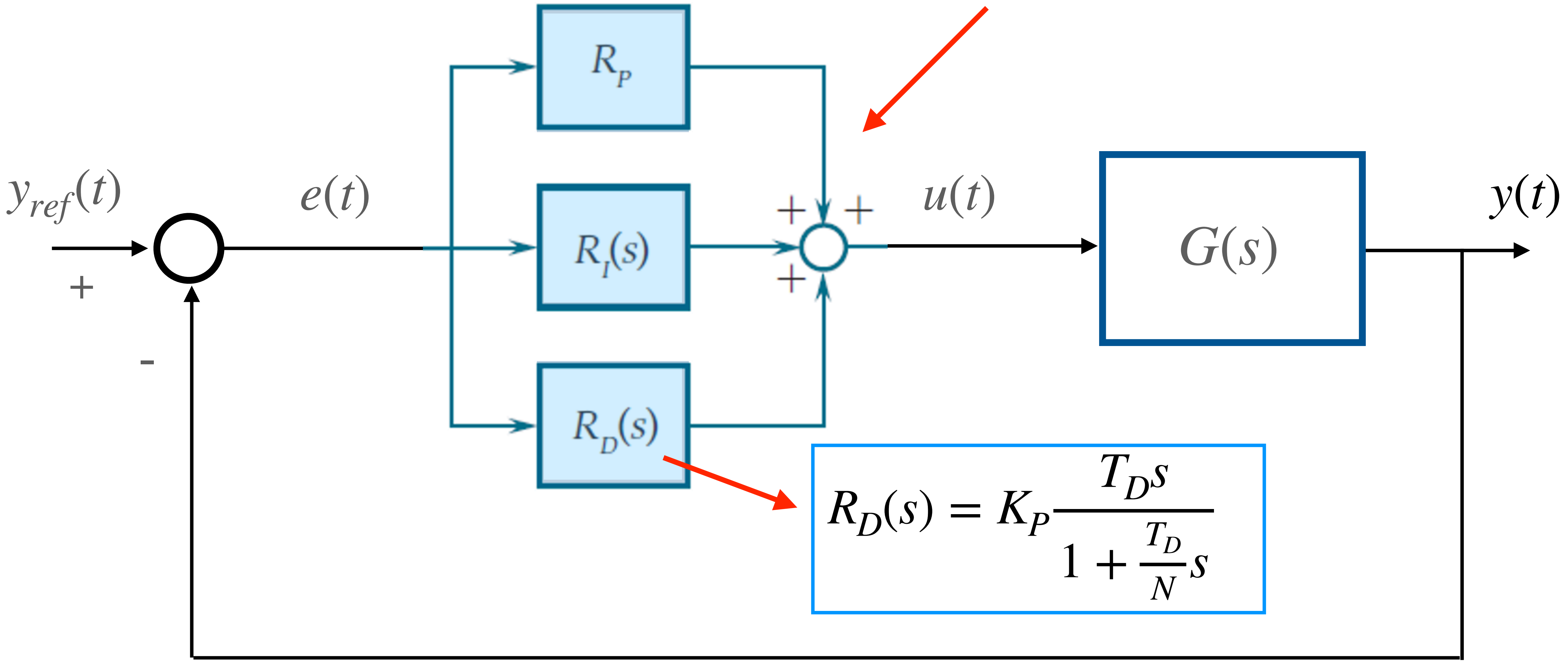

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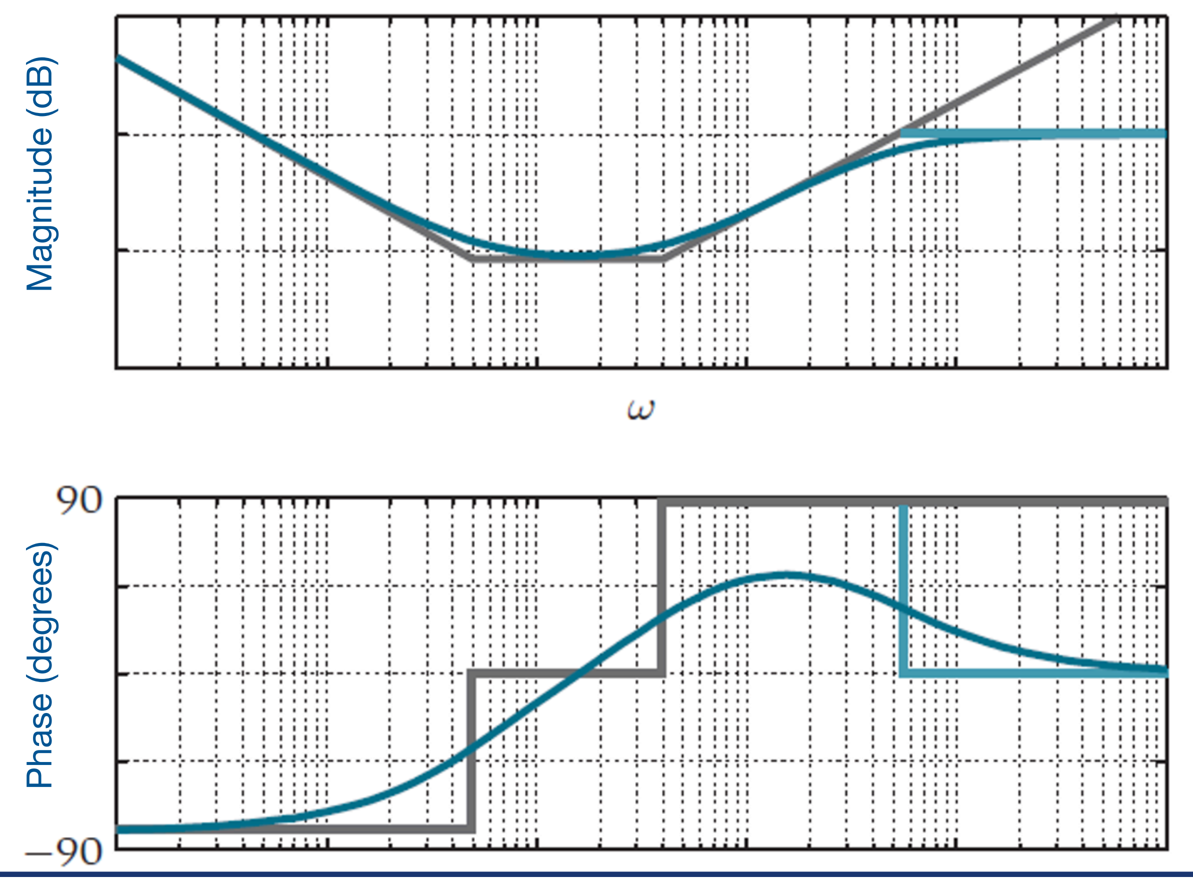
It is causal

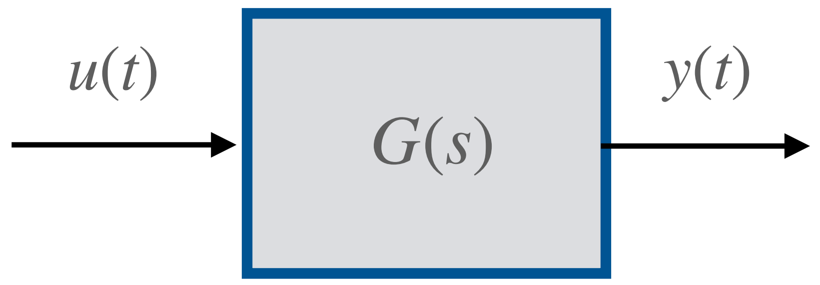
$$R_{PID}(s) = K_P \left(1 + \frac{1}{T_I s} + \frac{T_D s}{\boxed{1 + \frac{T_D}{N} s}}\right)$$

Effect of the new pole on the Bode plots



Design of PID Controllers

Process



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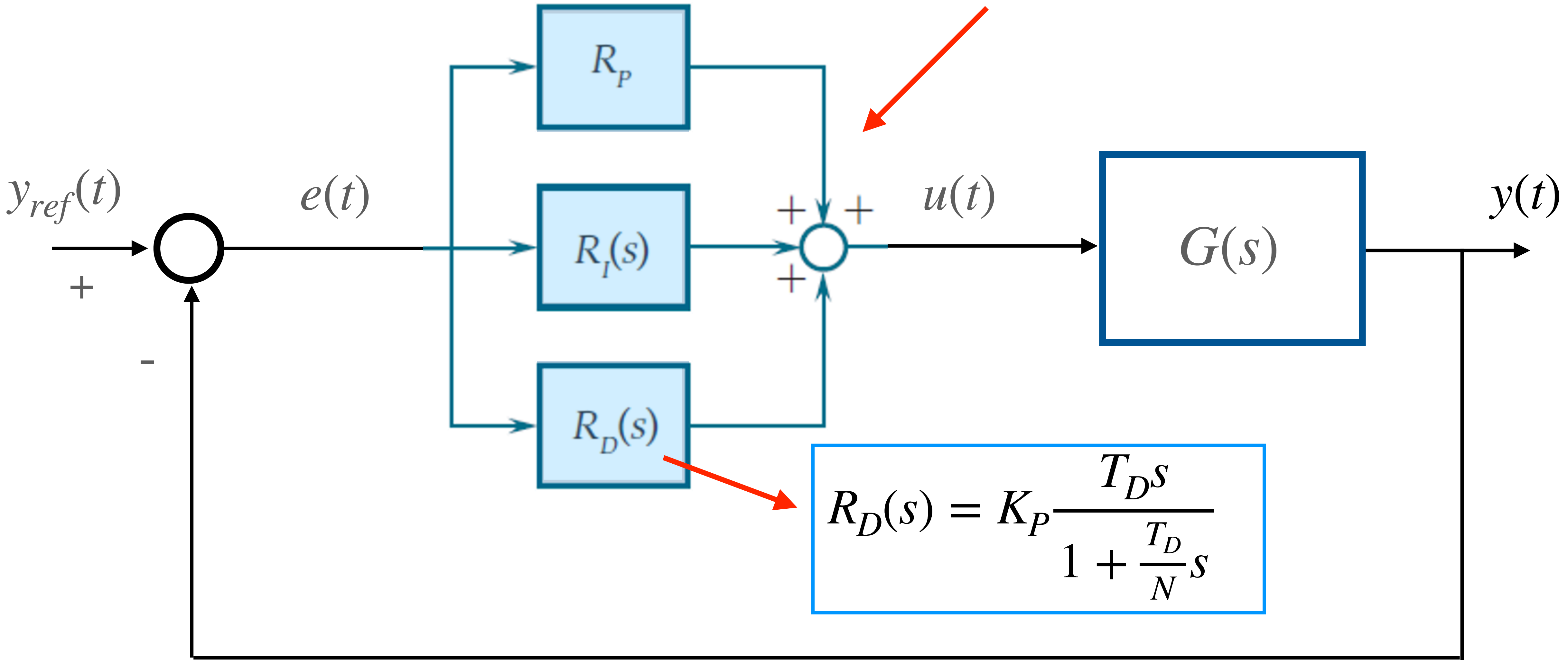
PID Controller: causal version



Alternative representation:

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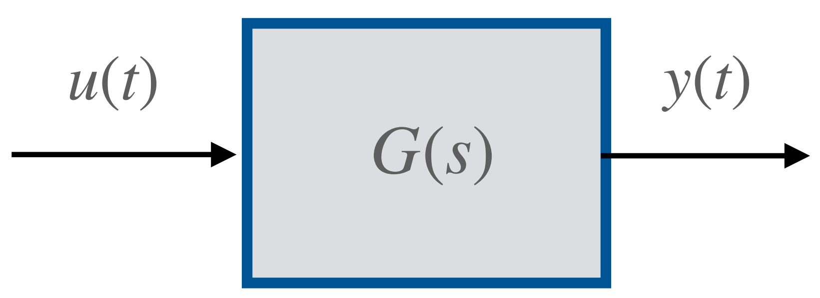
Effect of the new pole on the PID zeros:

It is causal

$$R_{PID}(s) = K_P \left(1 + \frac{1}{T_I s} + \frac{T_D s}{1 + \frac{T_D}{N} s}\right) \longrightarrow R_{PID}(s) = K_P \left(1 + \frac{1}{T_I s} + \frac{T_D N s}{T_D s + N}\right) = \frac{K_P \left[T_D s^2 + \left(1 + \frac{T_D}{T_I}\right) s + \frac{1}{T_I} N\right]}{s(T_D s + N)}$$

Design of PID Controllers

Process



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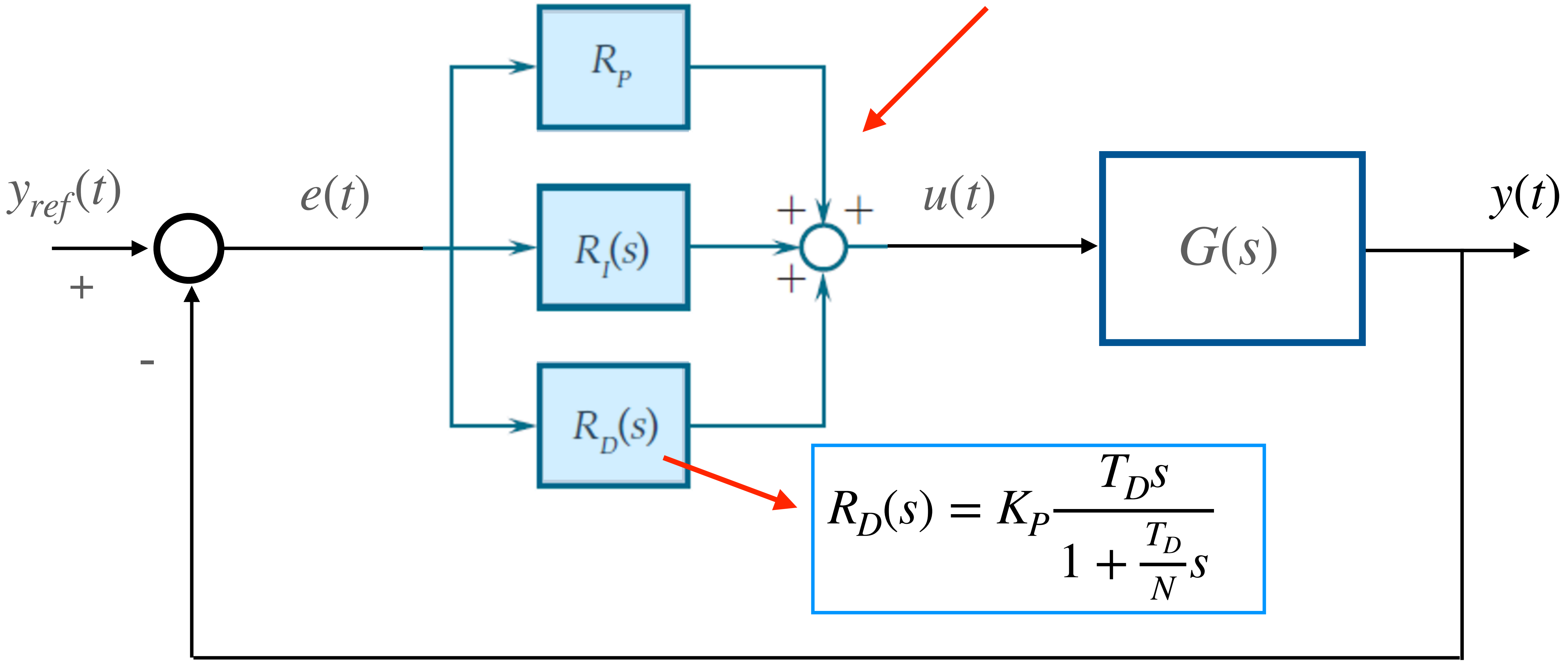
PID Controller: causal version



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Design of PID Controllers

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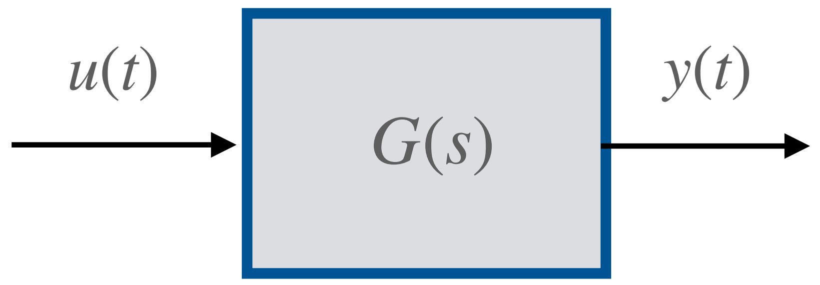

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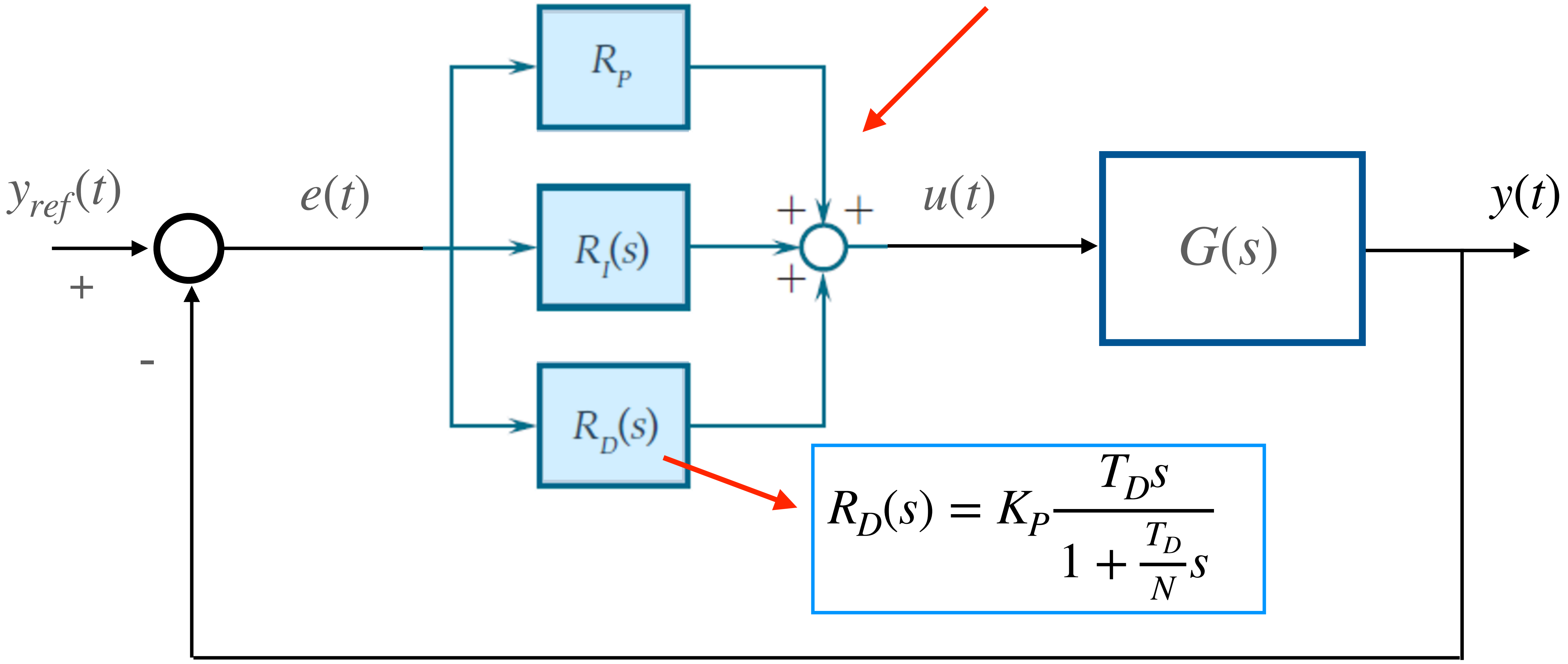

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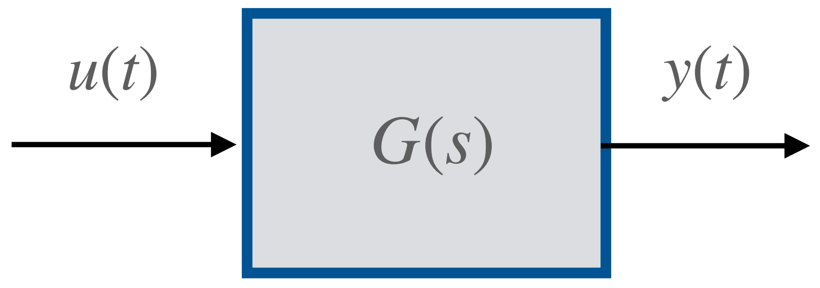
$N \to +\infty$ the zeros are practically the same as before

Design of PID Controllers

Process



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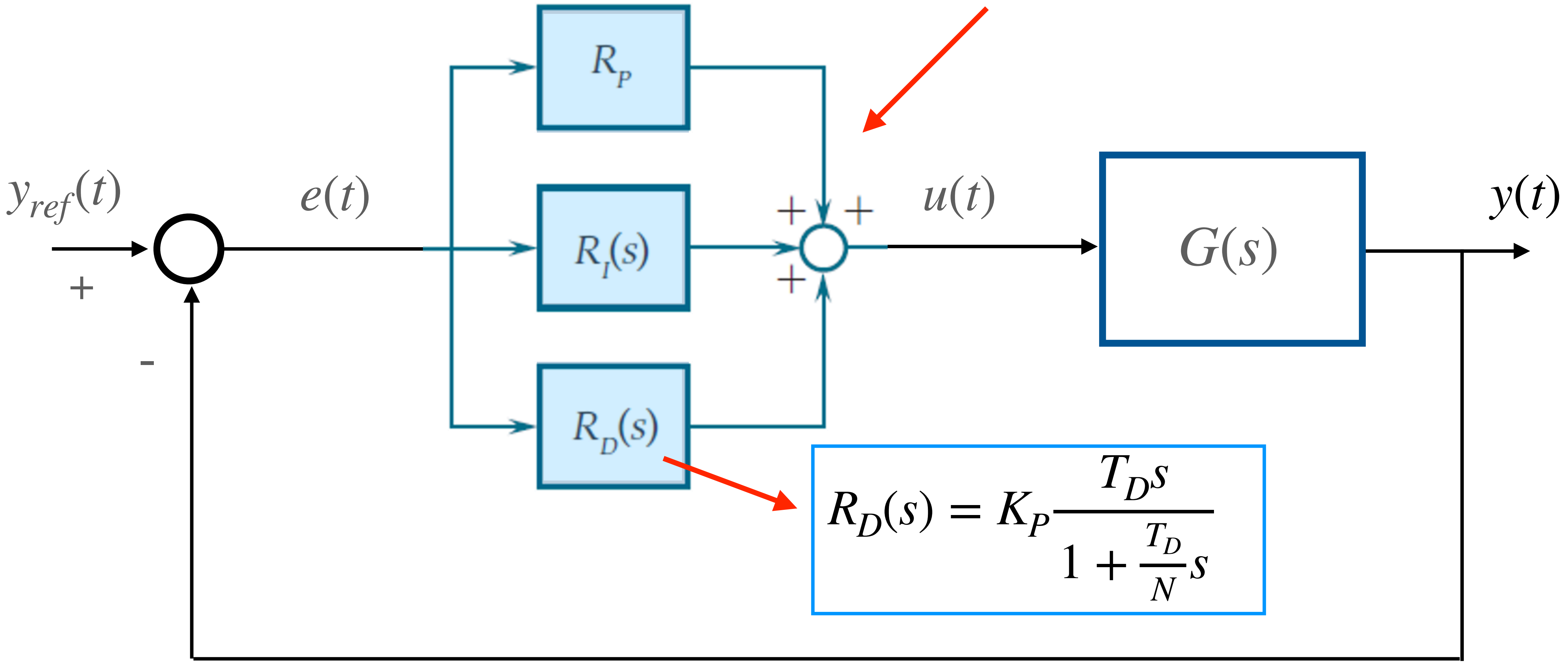
PID Controller: causal version



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Effect of the new pole on the PID zeros:

when $T_I = 4T_D$ the zeros coincide in $s = -\dfrac{1}{2T_D}$

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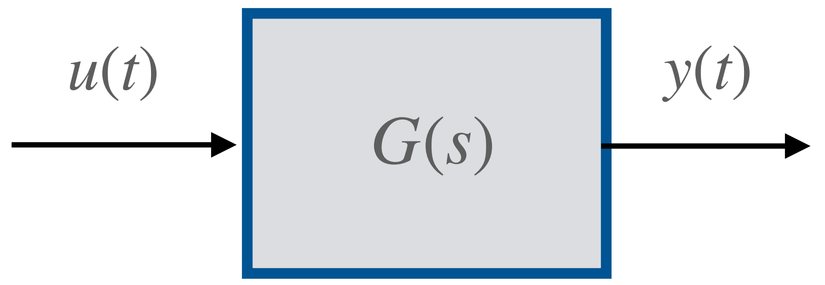
Design of PID Controllers

Process



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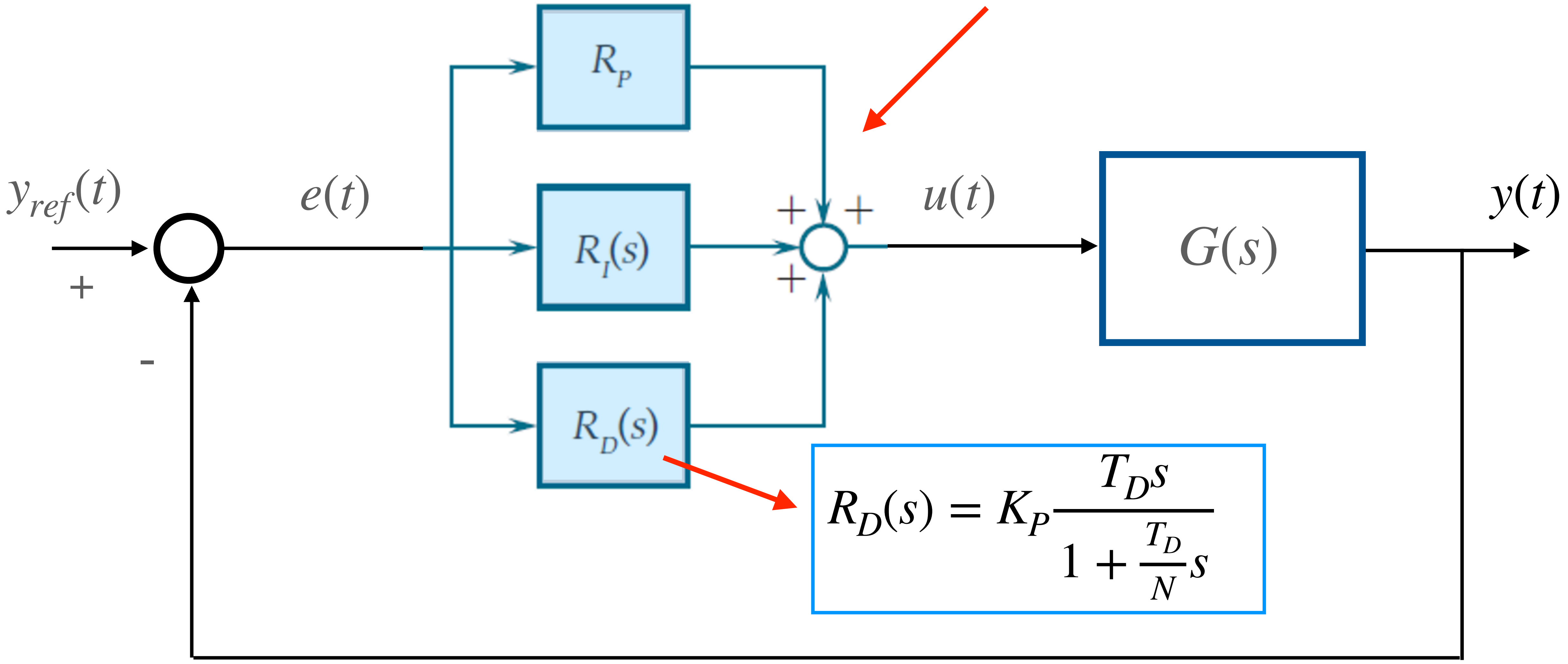

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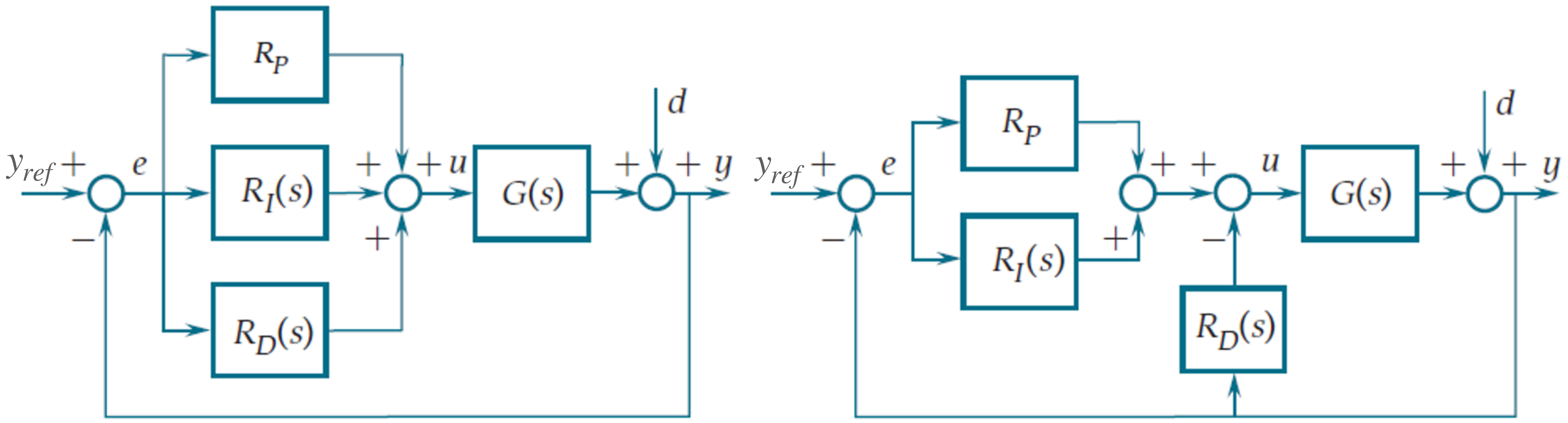
choice made to simplify PID parameter tuning

Practical Implementation of PID Controllers



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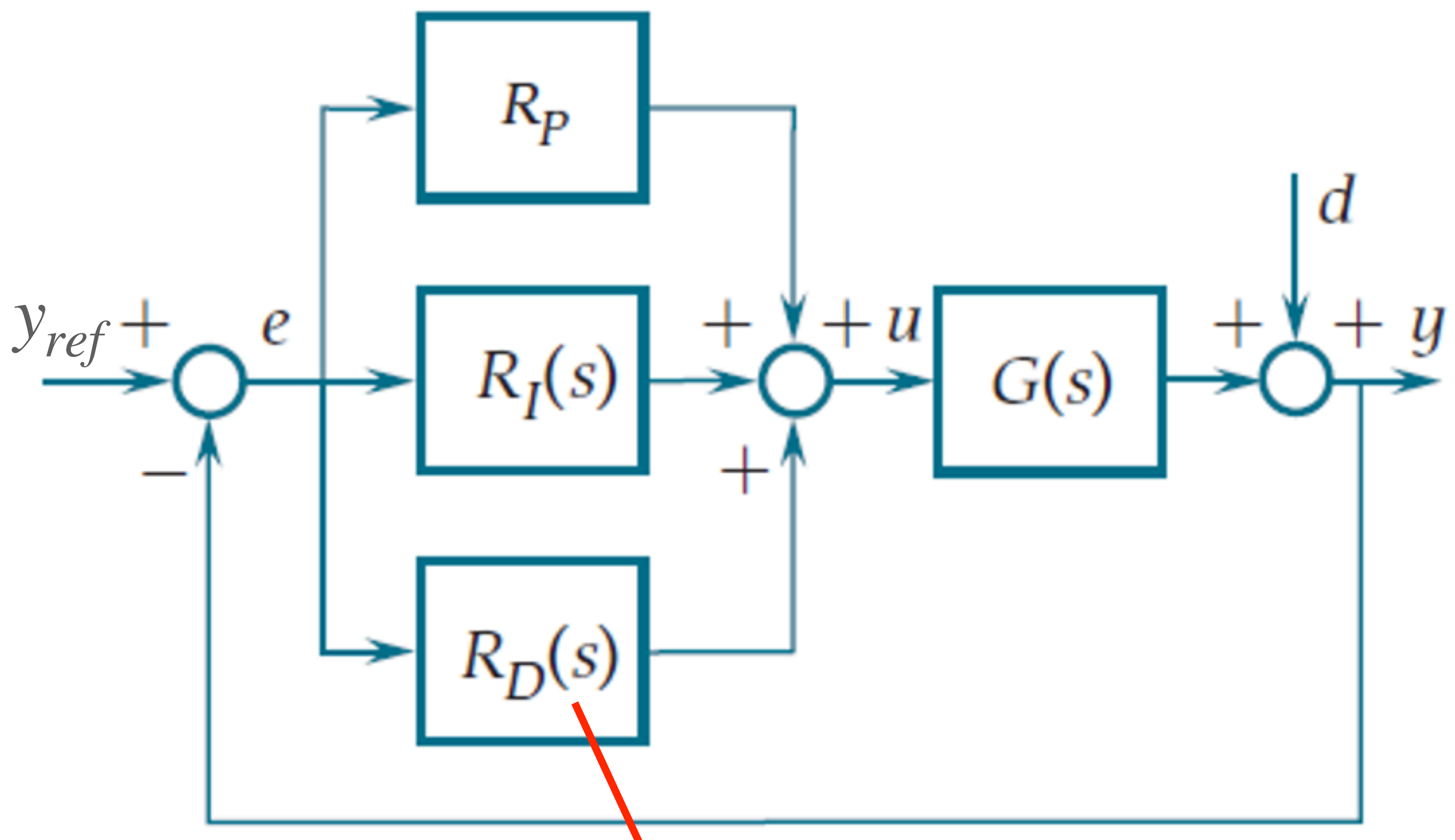

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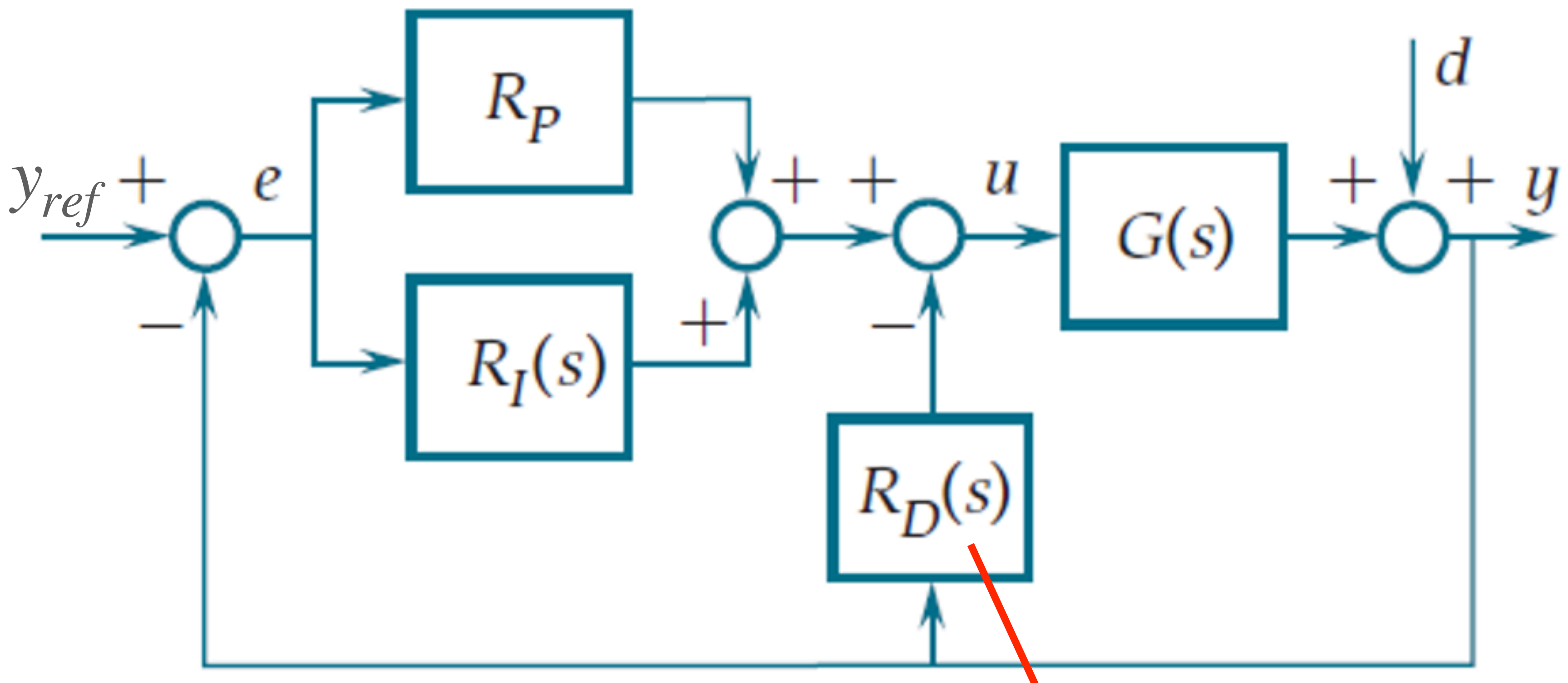
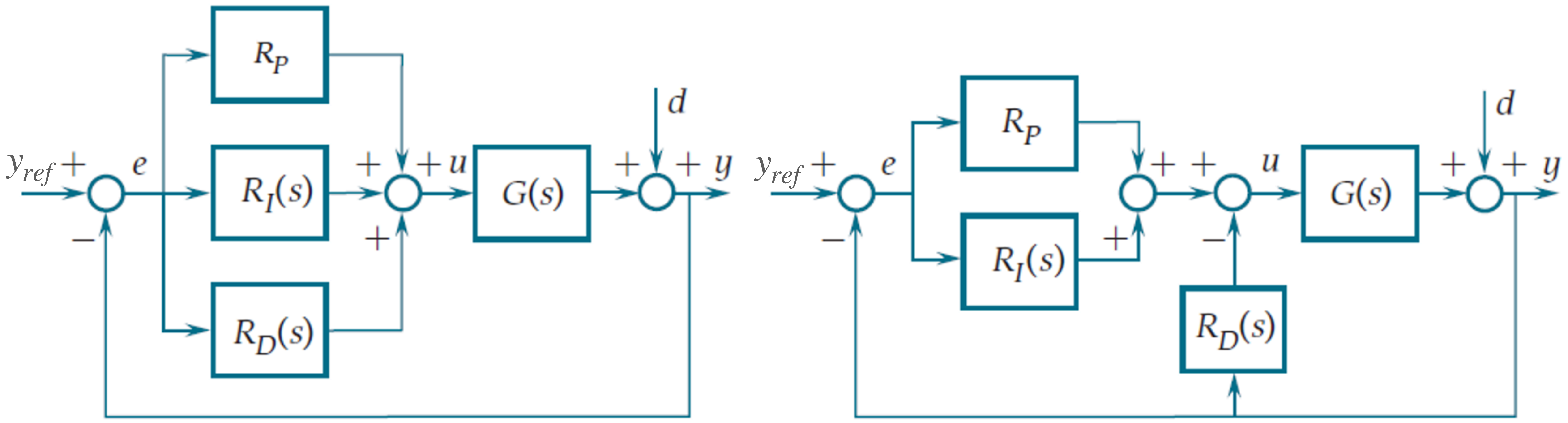
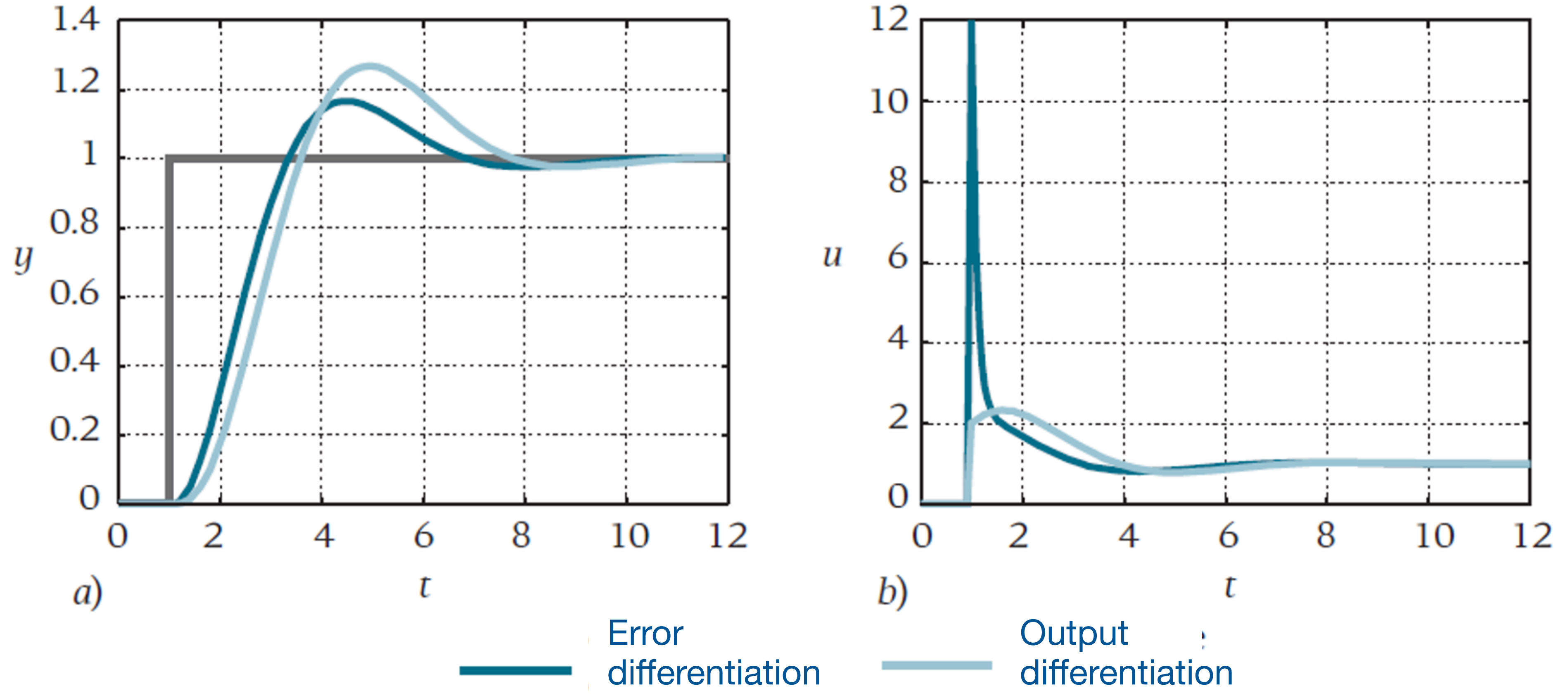


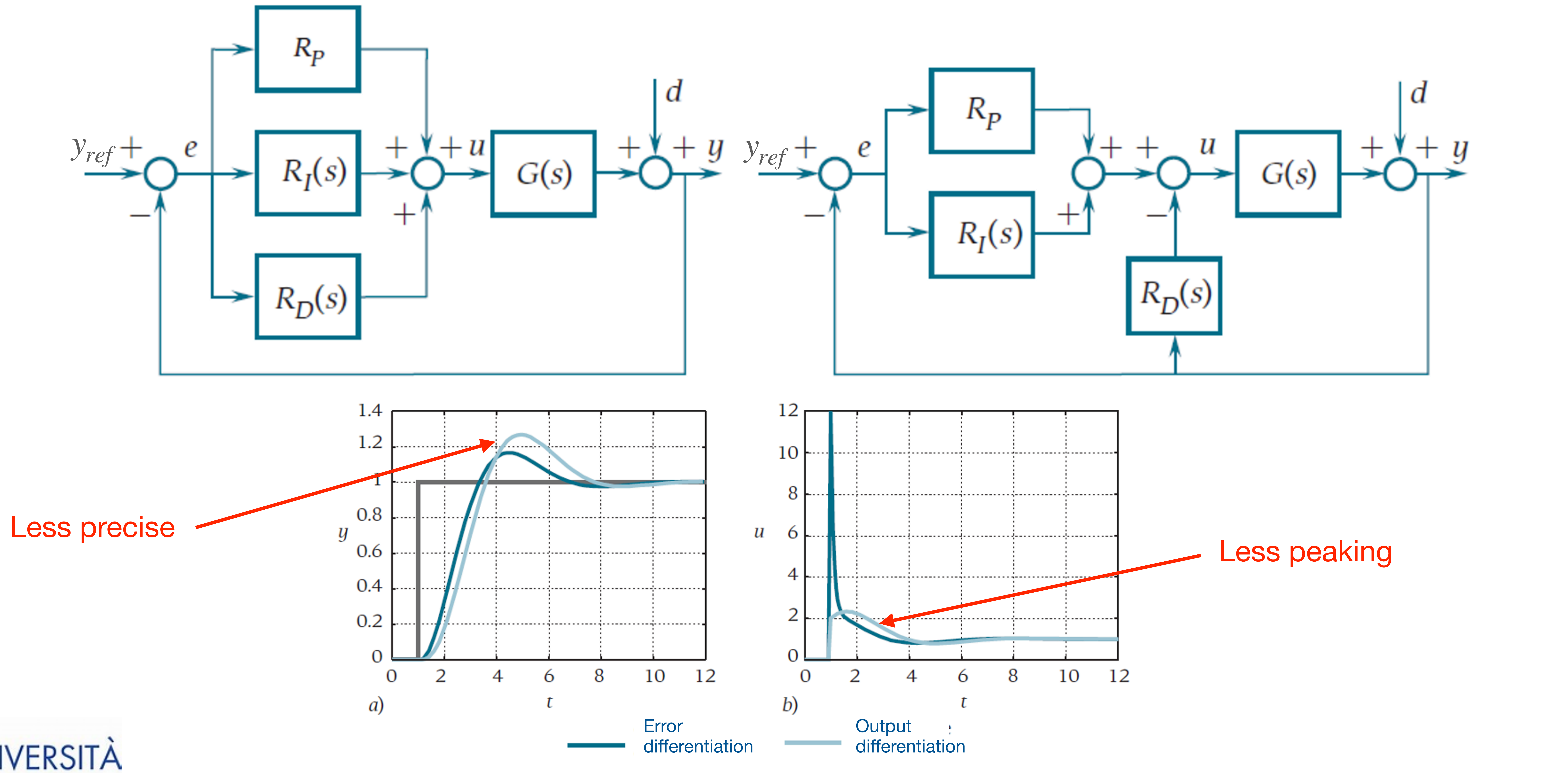
$$R_D(s) = K_P \frac{T_D s}{1 + \frac{T_D}{N} s}$$

Practical Implementation of PID Controllers

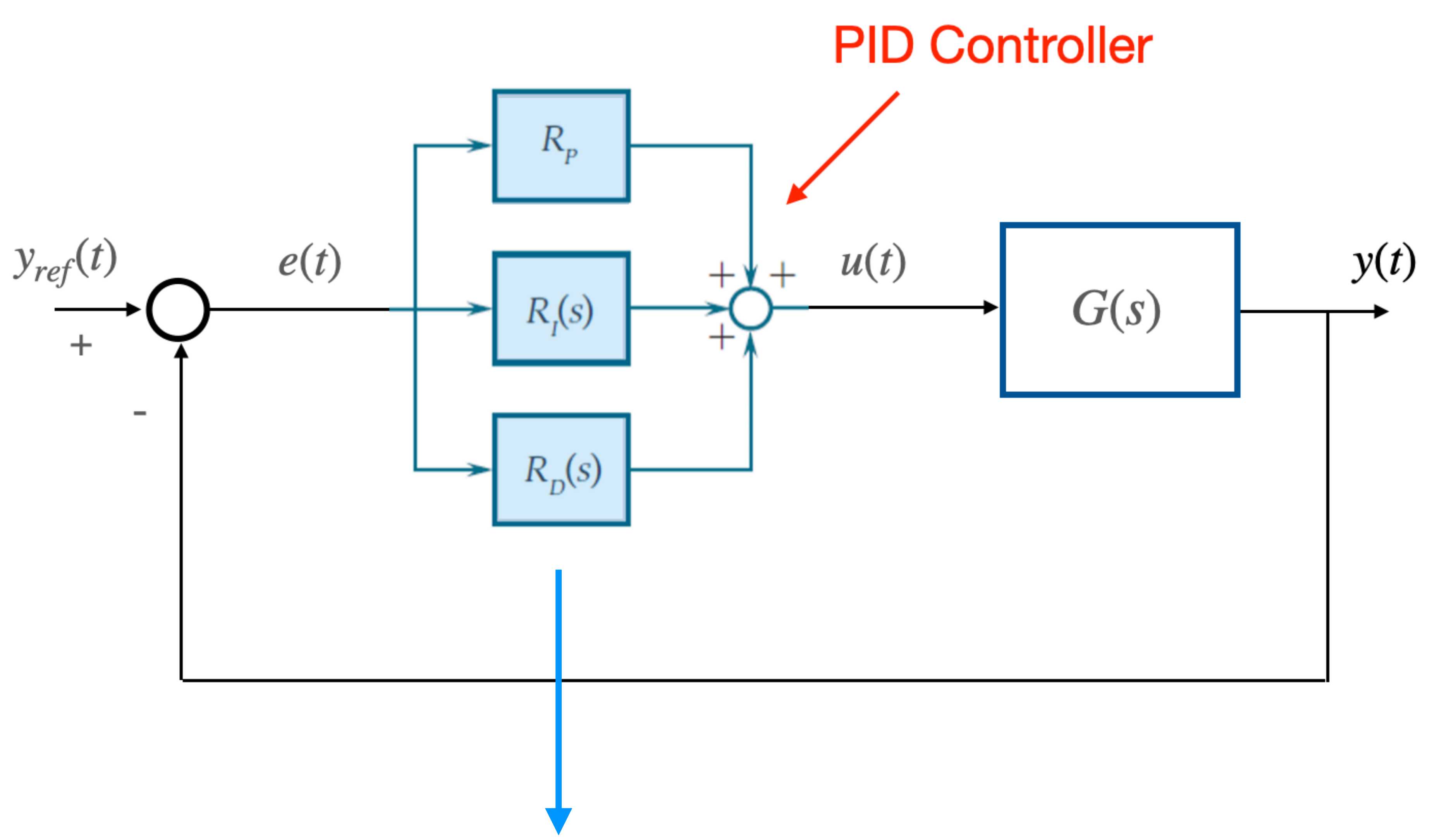




Practical Implementation of PID Controllers



Practical Implementation of PID Controllers: Tuning Rules

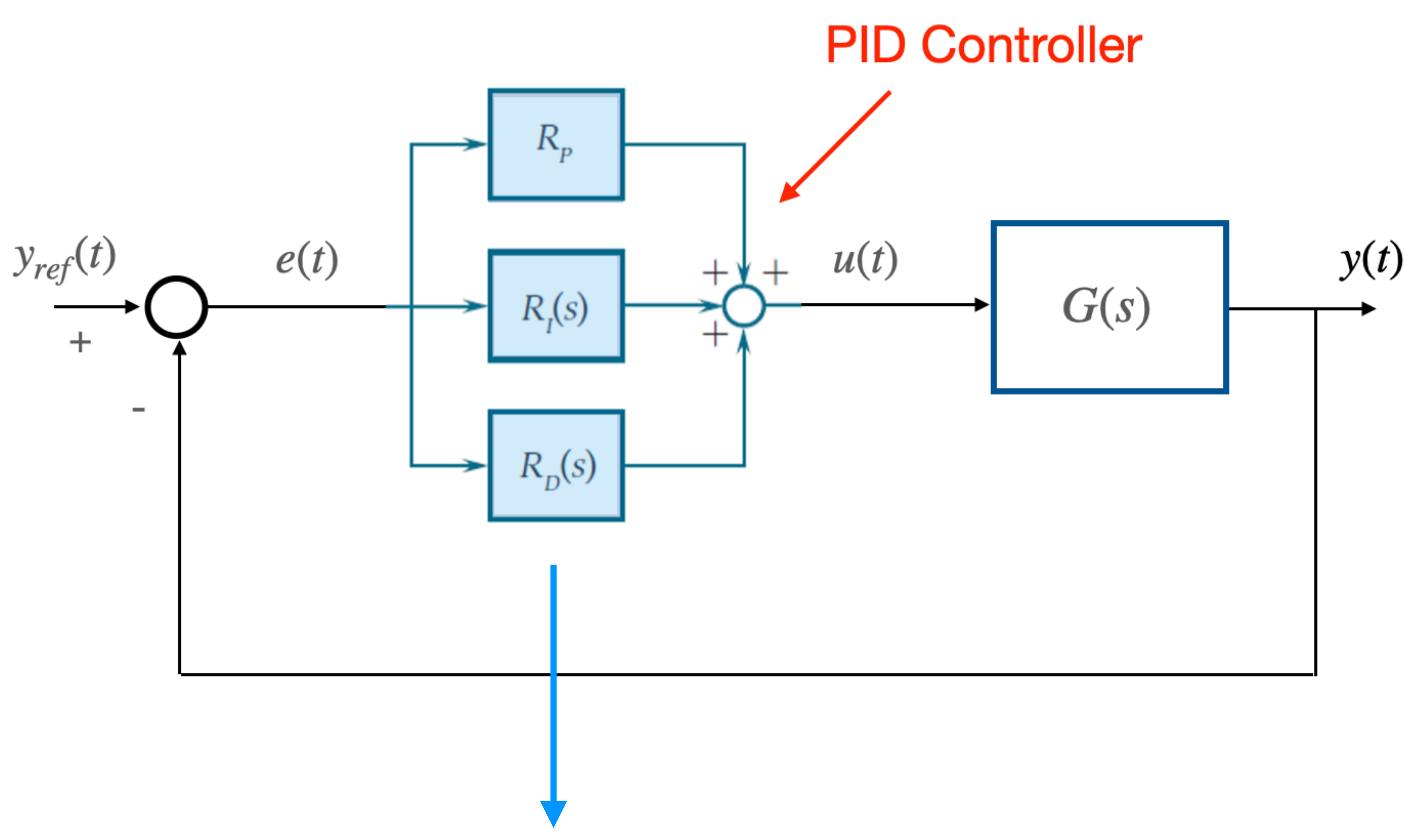


Testing phase:

$$R_P(s) = K_P, \quad R_I(s) = 1, \quad R_D(s) = 1$$

Closed-loop Ziegler-Nichols Method

Practical Implementation of PID Controllers: Tuning Rules



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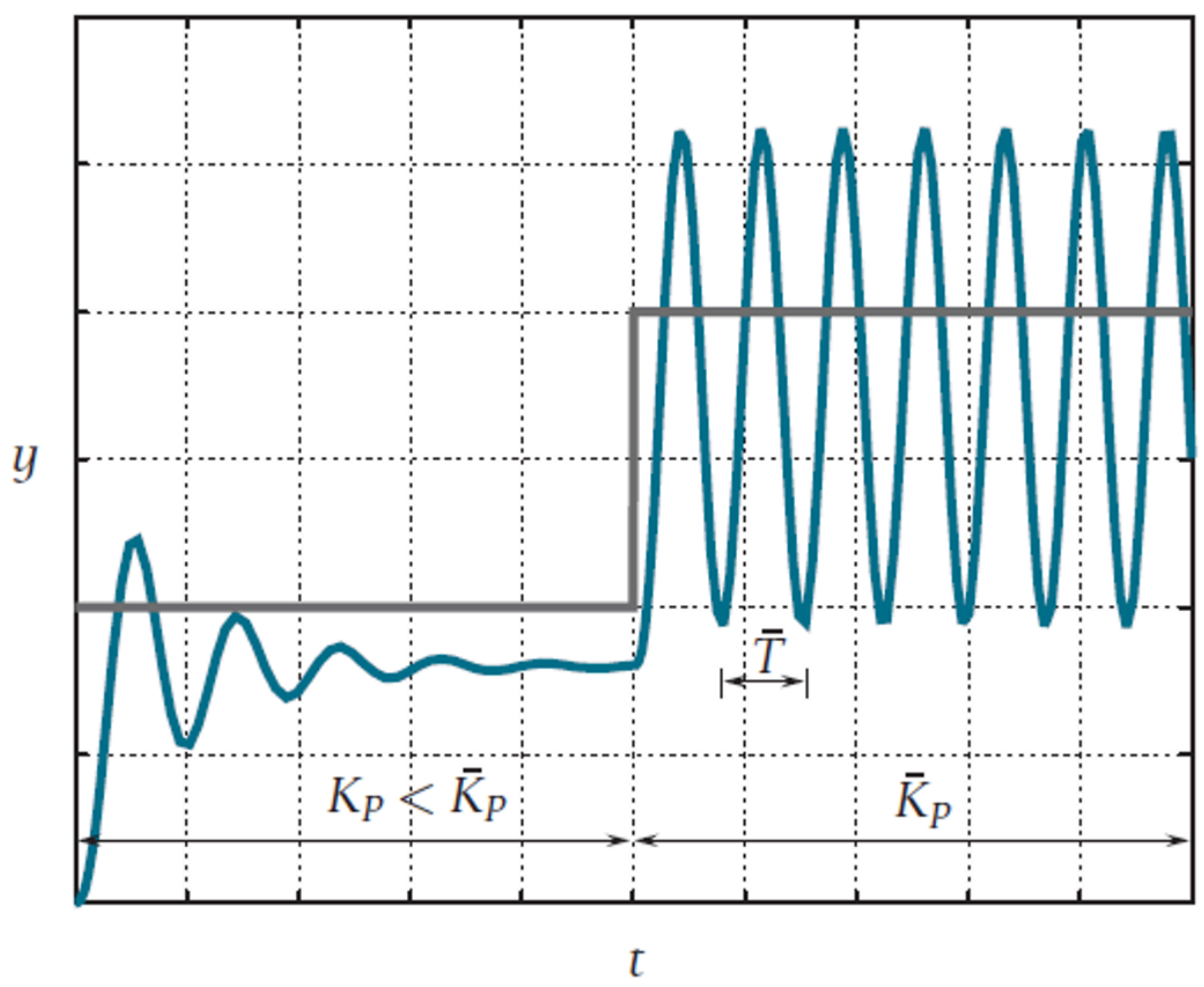
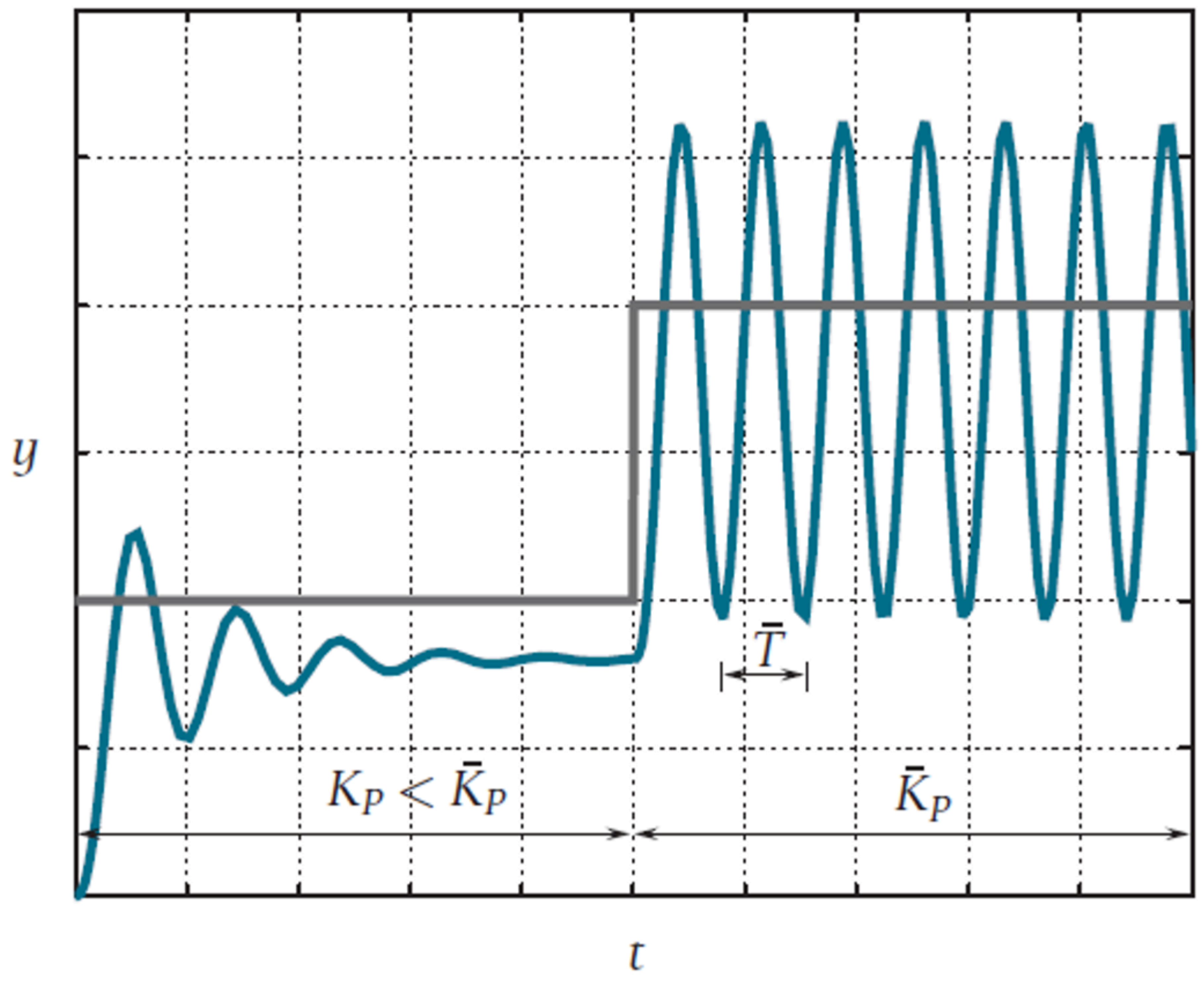


Practical Implementation of PID Controllers: Tuning Rules

Closed-loop Ziegler-Nichols Method

	K_P	T_I	T_D
P	$0.5\overline{K}_P$		
PI	$0.45\overline{K}_P$	$0.8\overline{T}$	
PID	$0.6\overline{K}_P$	$0.5\overline{T}$	$0.125\overline{T}$

$$R_{PID_{id}}(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$



Practical Implementation of PID Controllers: Tuning Rules

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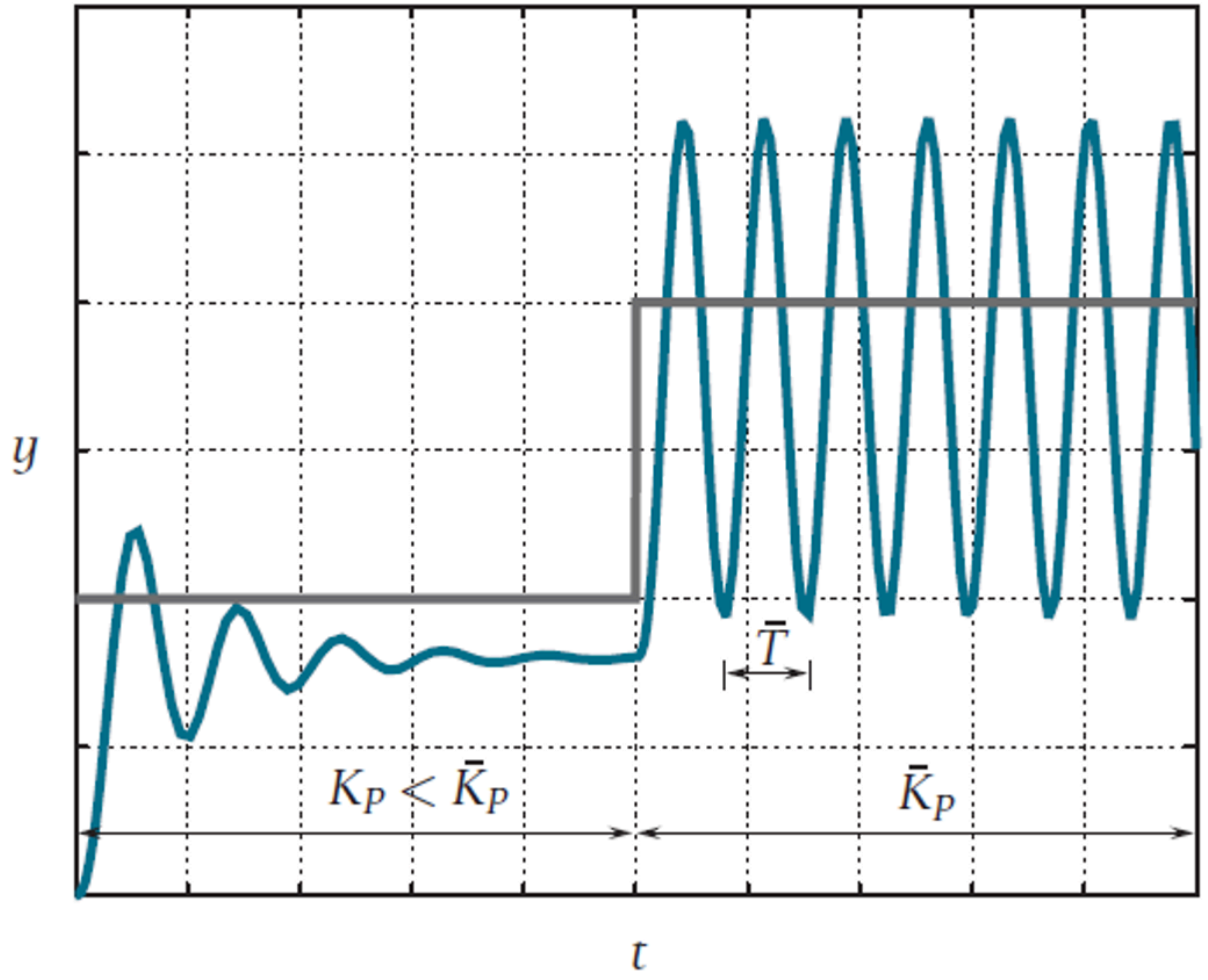

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Note that $T_I = 4T_D$ $\rightarrow$ the PID zeros coincide in $s = -\dfrac{1}{2T_D}$

Practical Implementation of PID Controllers: Tuning Rules

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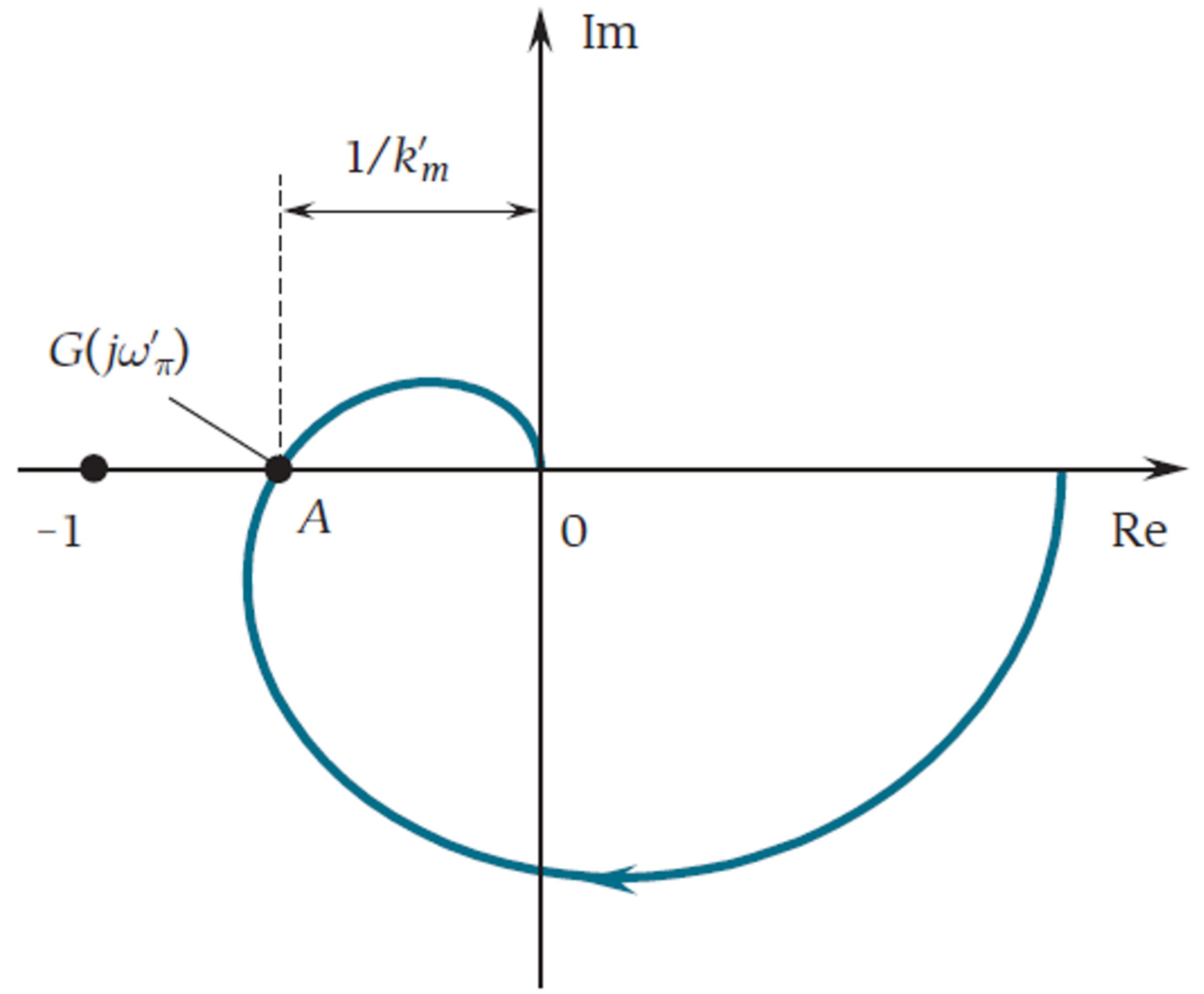
Closed-loop Ziegler-Nichols Method: Interpretation



$\bar{K}_p = k'_m$ $\rightarrow$ Gain Margin of $G(s)$

$\bar{T} = \dfrac{\pi}{\omega'_\pi}$ $\rightarrow$ where ω'_π is the pulse corresponding to point A

Practical Implementation of PID Controllers: Tuning Rules

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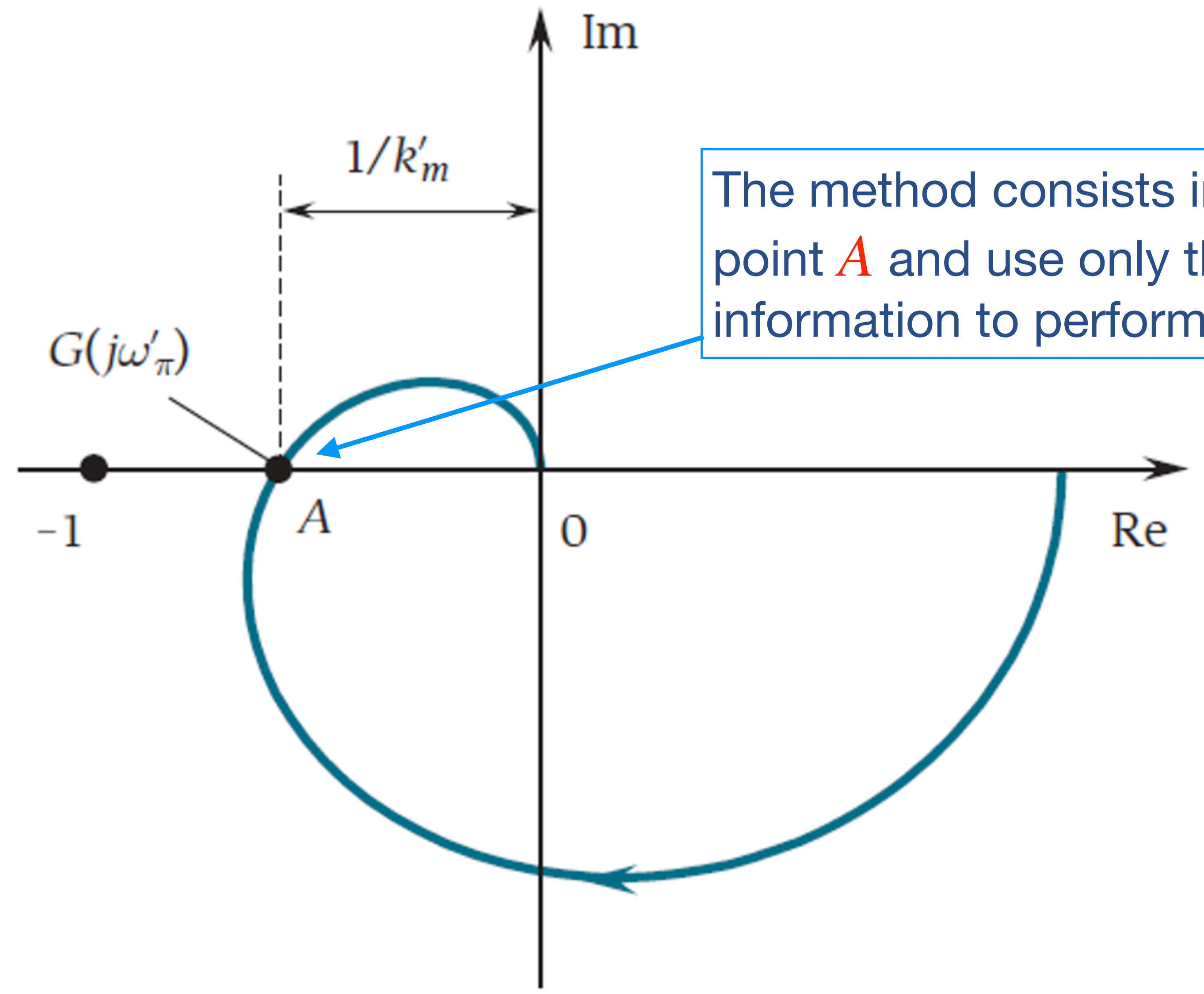

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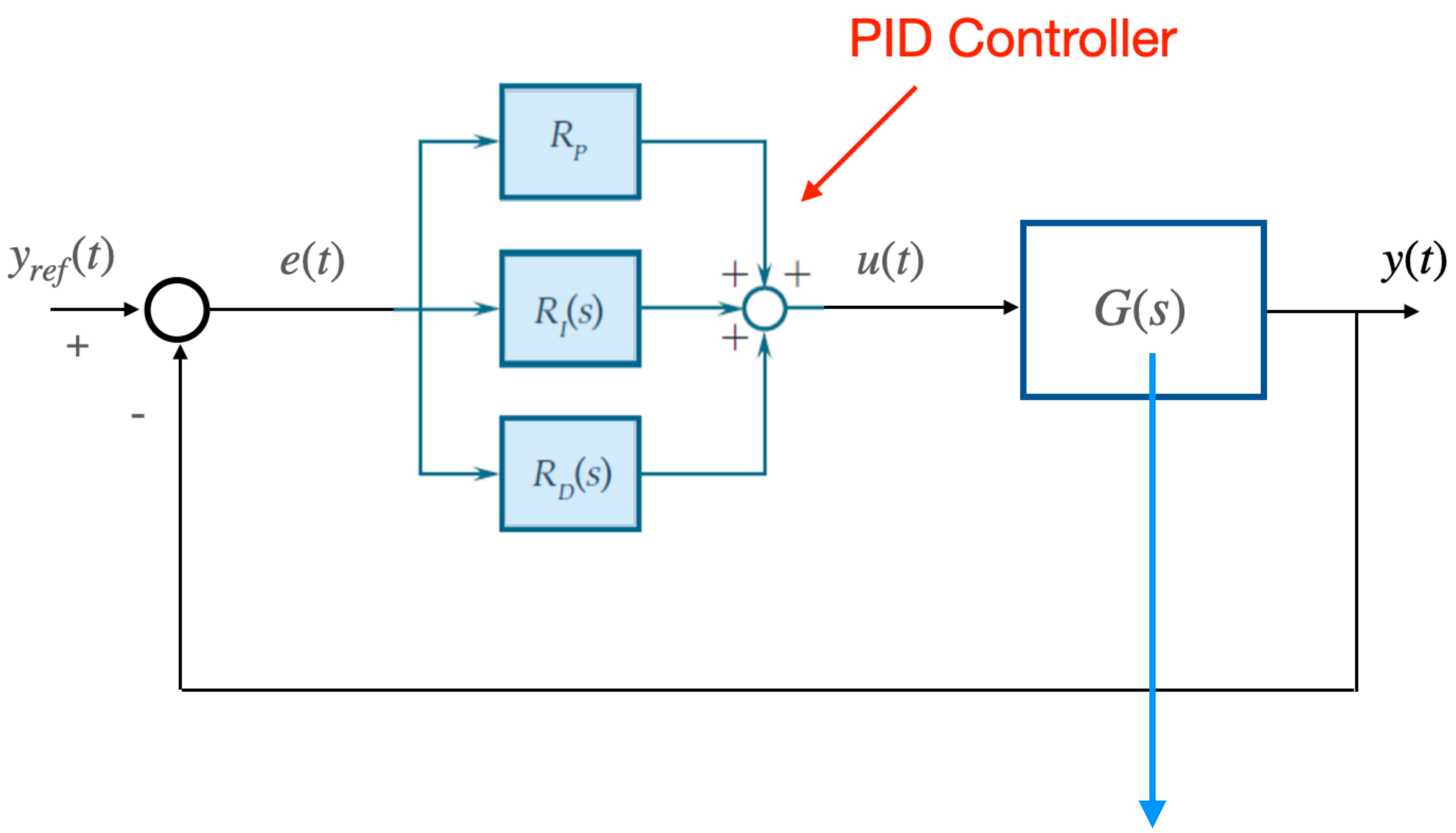
Practical Implementation of PID Controllers: Tuning Rules

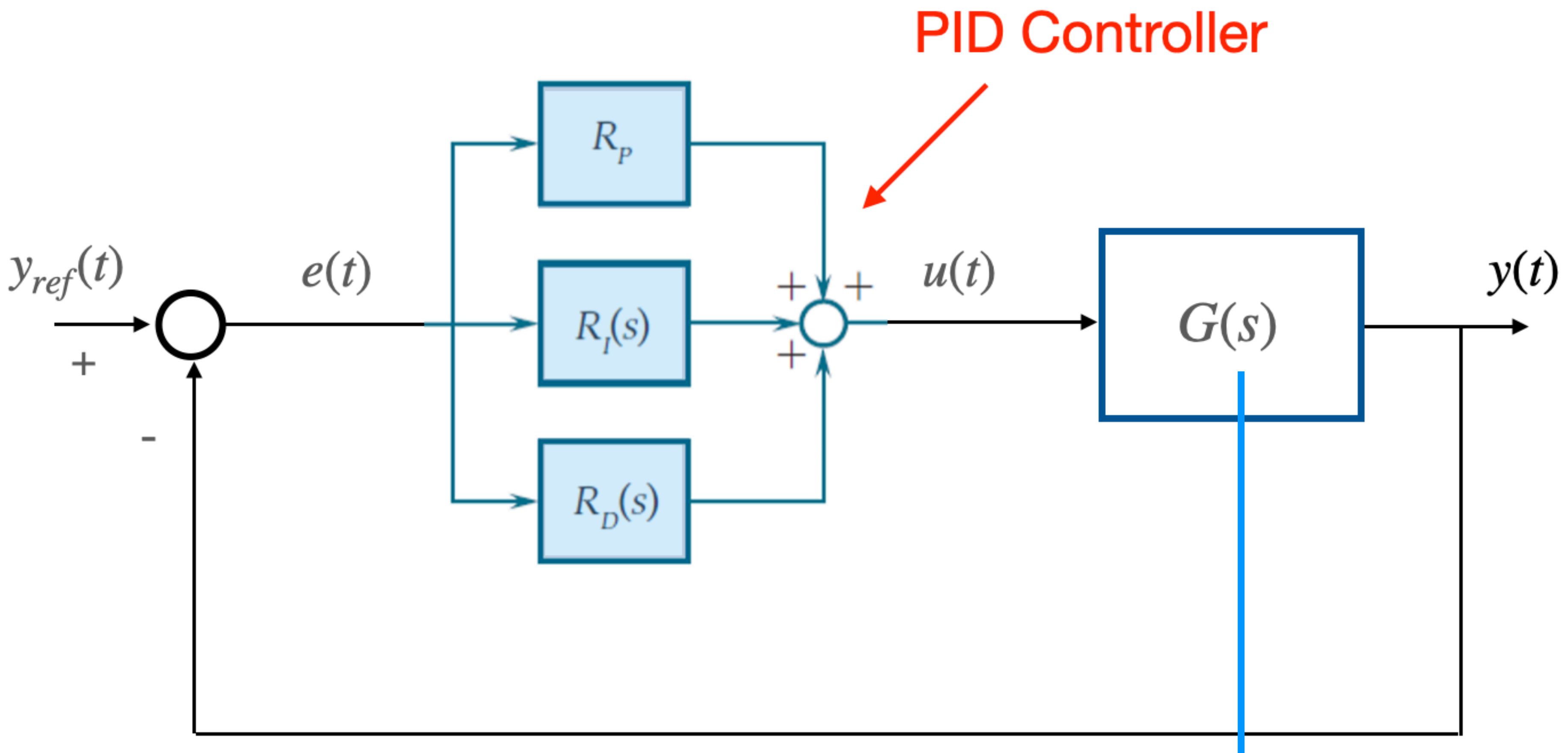
Open-loop Methods



Approximate Model of the Process:

$$G_a(s) = \frac{\mu\, e^{-\tau s}}{1 + Ts}$$

Practical Implementation of PID Controllers: Tuning Rules



Open-loop Methods

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equivalent delay

equivalent time-constant

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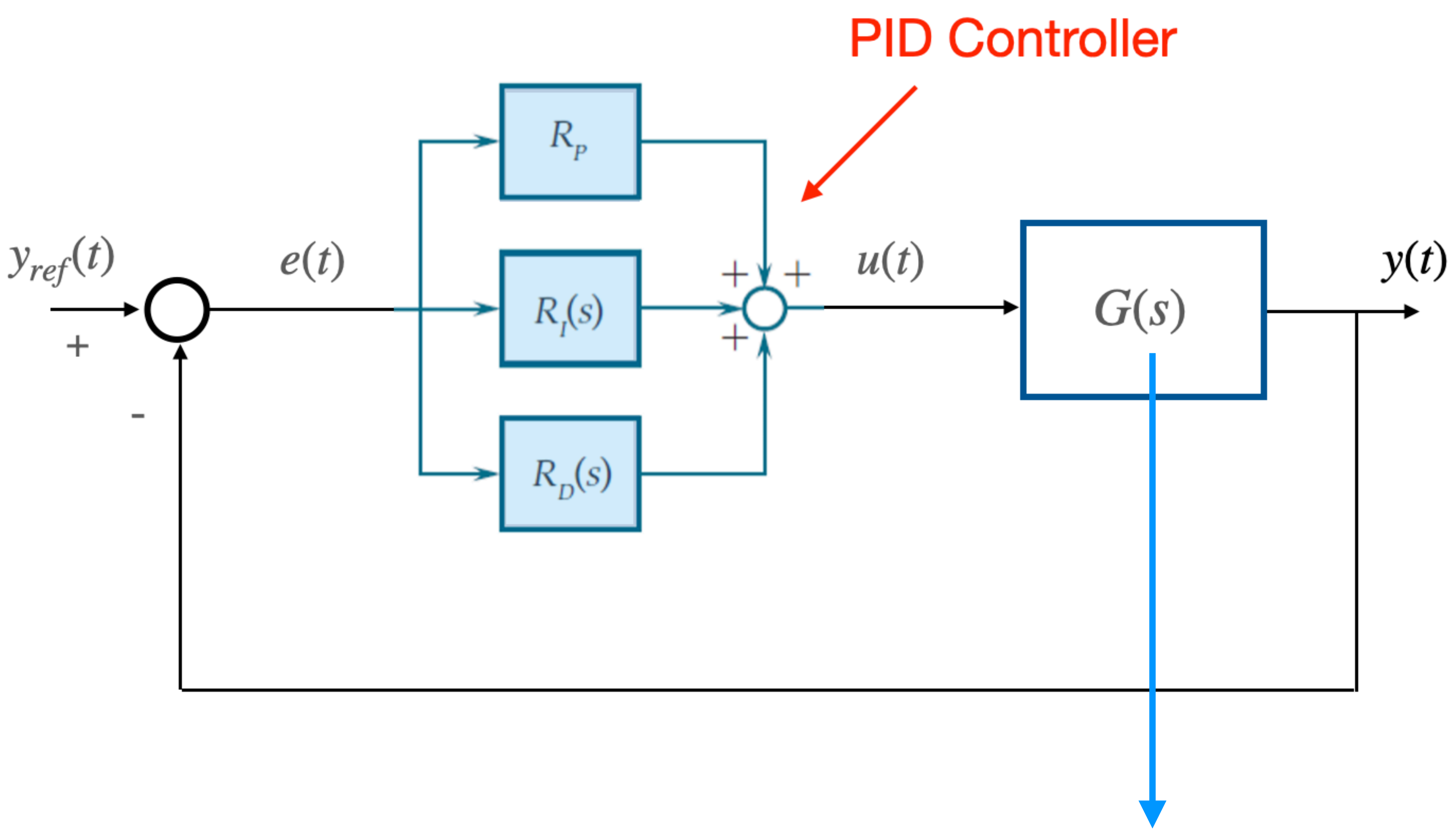

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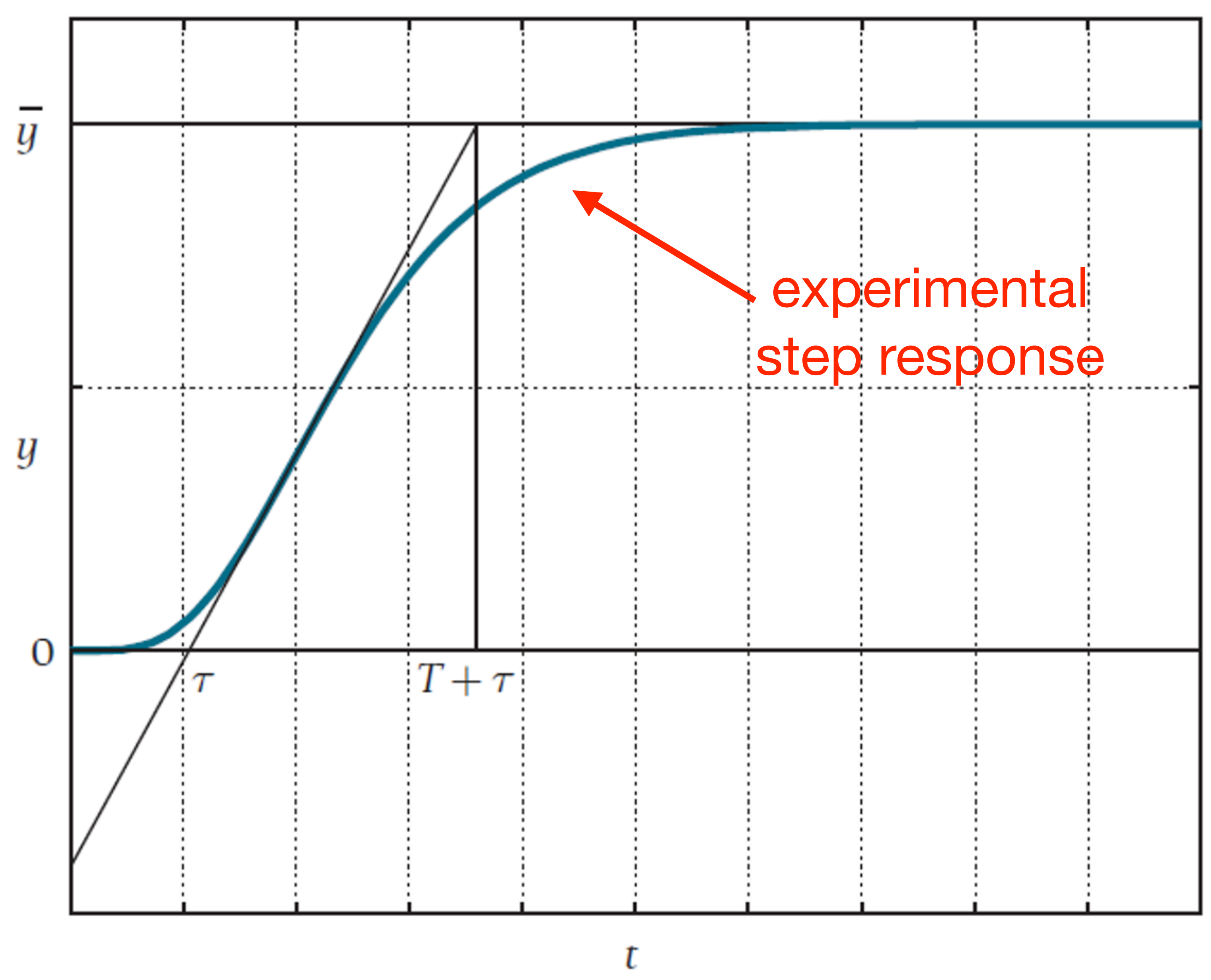
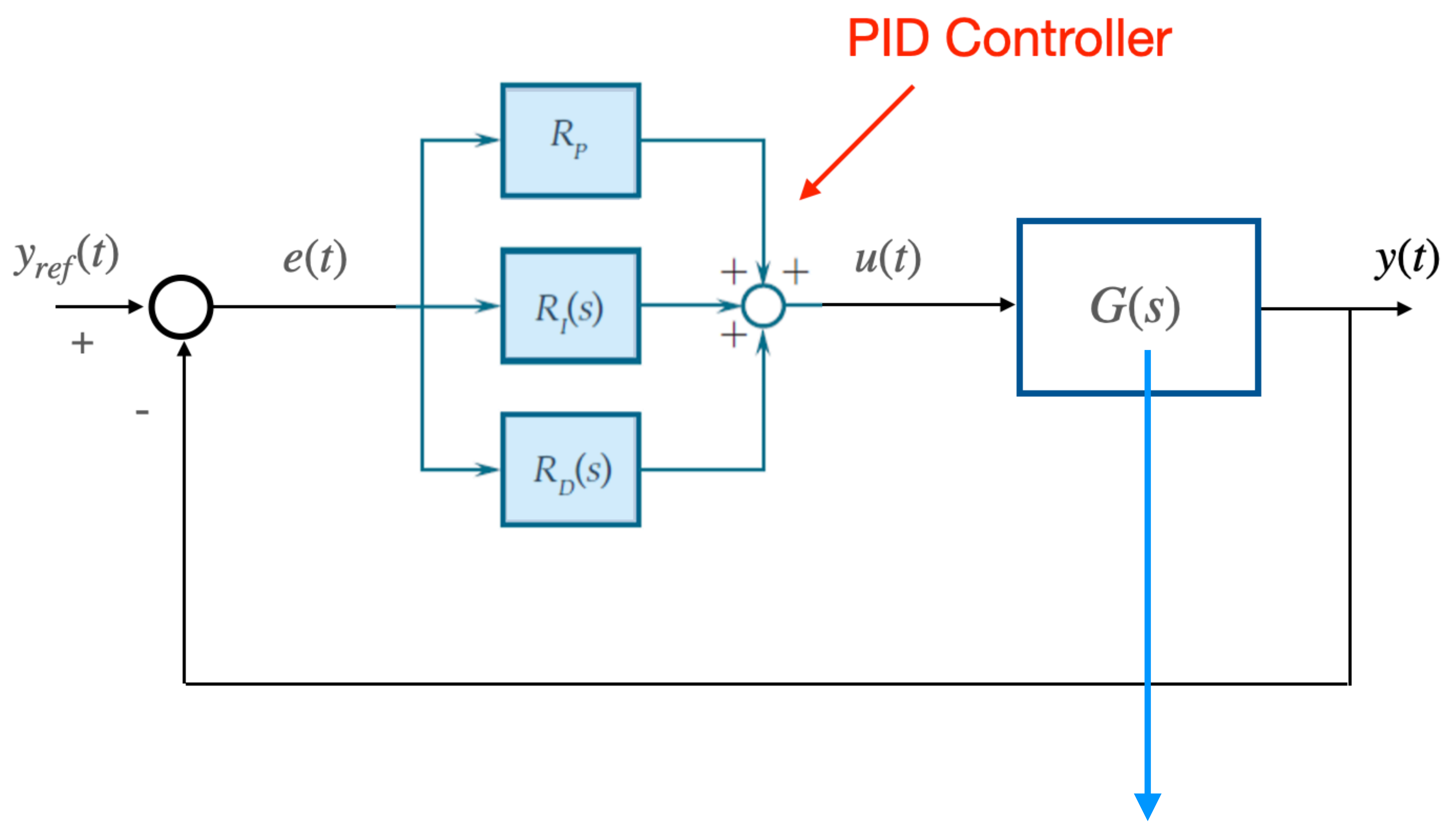
Open-loop Methods

Parameters τ, T determination via the Tangent Method



Practical Implementation of PID Controllers: Tuning Rules



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Open-loop Ziegler-Nichols Method

	K_P	T_I	T_D
P	$\frac{T}{\mu\tau}$		
PI	$\frac{0.9T}{\mu\tau}$	3τ	
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$$R_{PID_{id}}(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$

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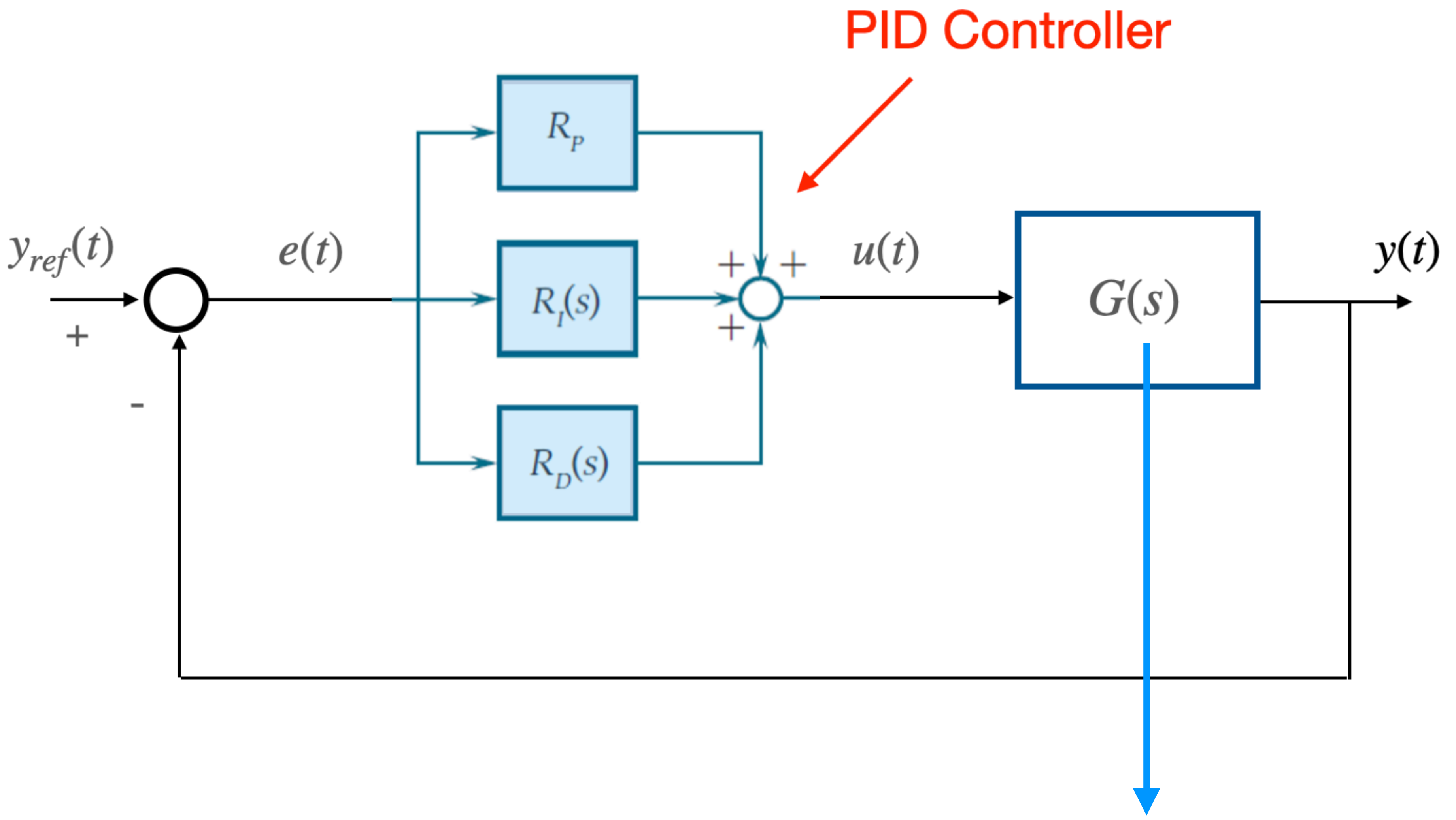

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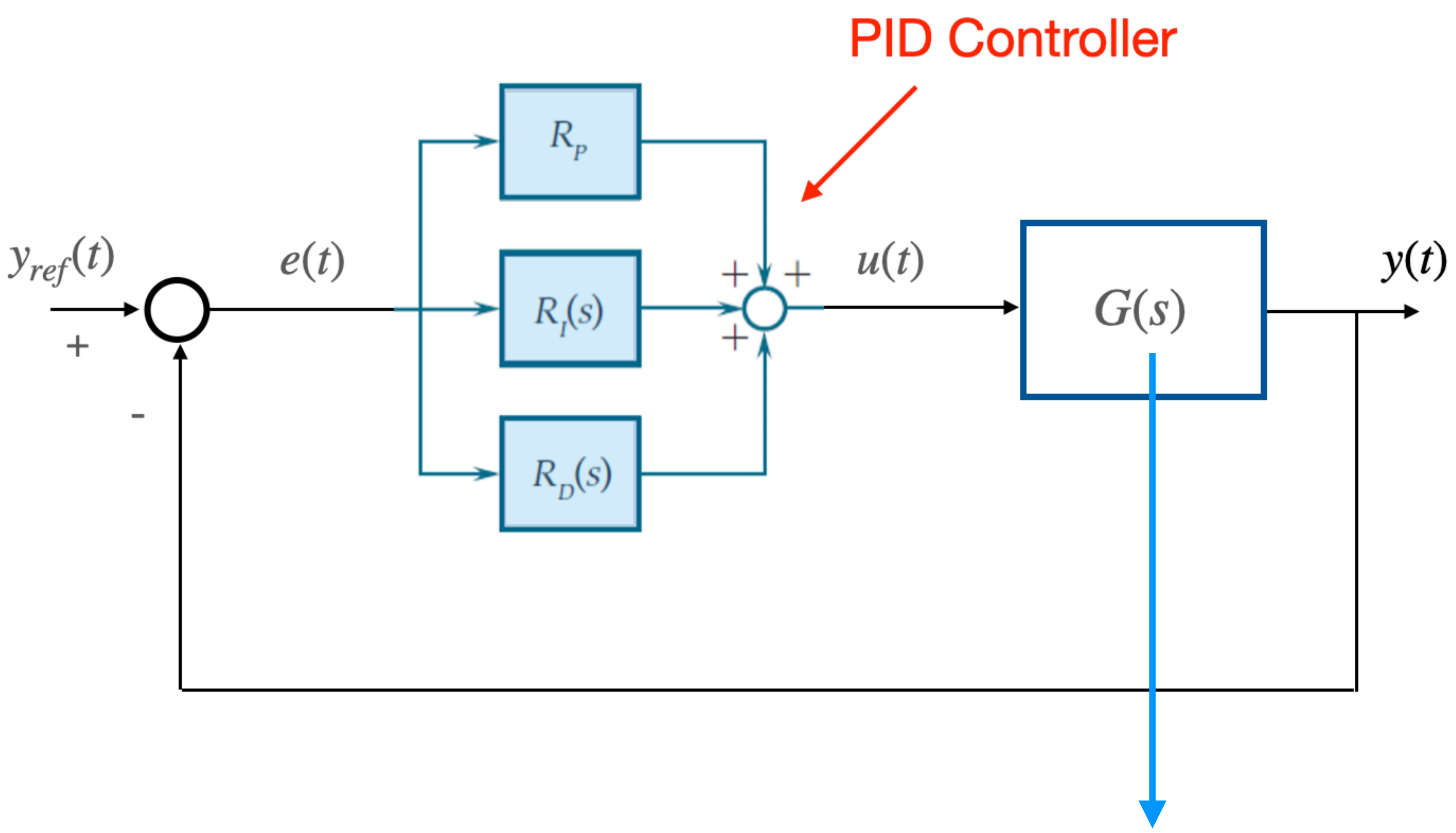
Practical Implementation of PID Controllers: Tuning Rules



Approximate Model of the Process:

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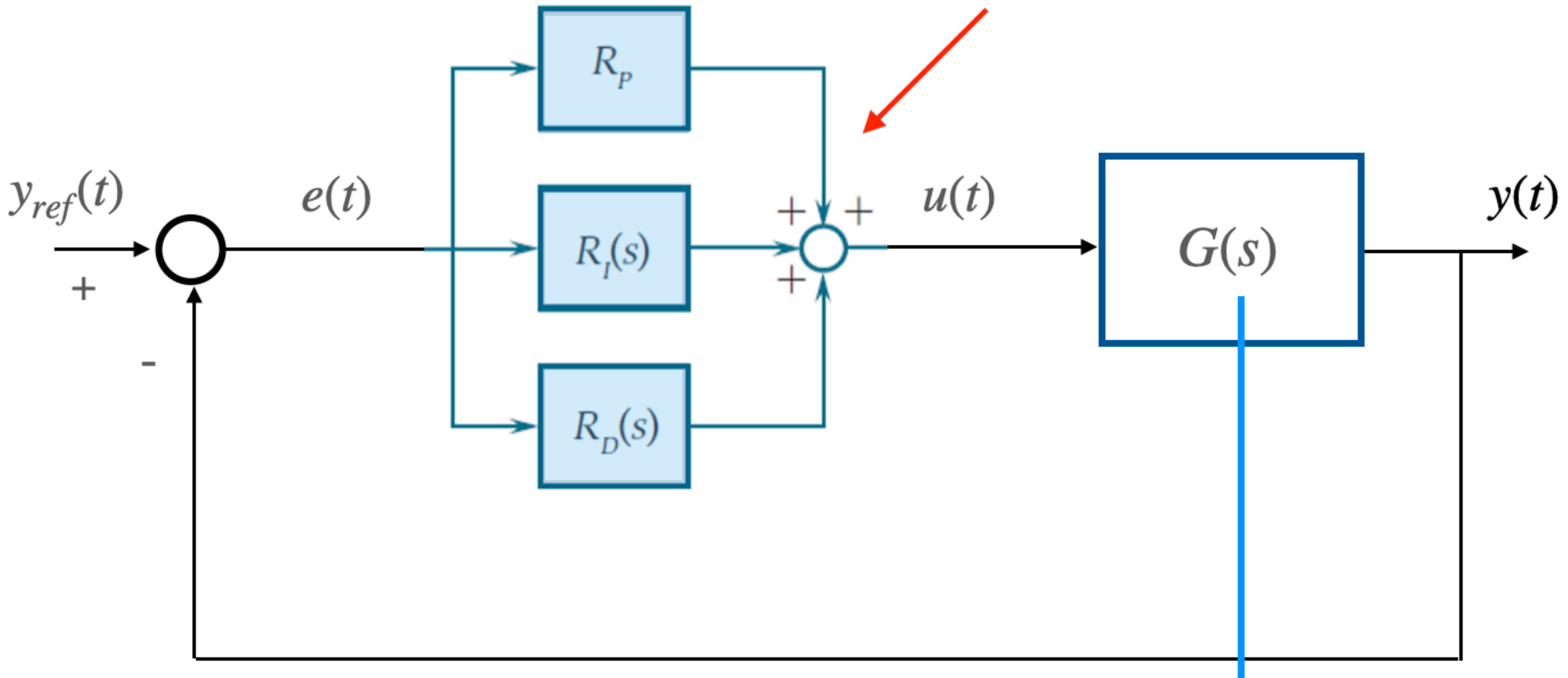
Open-loop Cohen-Coon Method

	K_P	T_I	T_D
P	$\frac{3T+\tau}{3\mu\tau}$		
PI	$\frac{10.8T+\tau}{12\mu\tau}$	$\tau\frac{30T+3\tau}{9T+20\tau}$	
PID	$\frac{16T+3\tau}{12\mu\tau}$	$\tau\frac{32T+6\tau}{12\tau}$	$\frac{4T\tau}{11T+2\tau}$

$$R_{PID_{id}}(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$

Practical Implementation of PID Controllers: Tuning Rules

PID Controller



Open-loop Internal Model Control (IMC) Method

	K_P	T_I	T_D
PI	$\dfrac{T}{\mu(\tau + T_f)}$	T	
PID	$\dfrac{T + 0.5\tau}{\mu(T_f + 0.5\tau)}$	$T + 0.5\tau$	$\dfrac{0.5\tau T}{T + 0.5\tau}$

Approximate Model of the Process:

$$G_a(s) = \frac{\mu\, e^{-\tau s}}{1 + Ts}$$

$$R_{PID_{id}}(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$

additional parameters: if T_f increases, then $\omega_{BW_{CL}}$ decreases and the chase and gain margins increase

Practical Implementation of PID Controllers: Tuning Rules

Comparison:

	φ_m	k_m	ω_c
Cohen - Coon	31°	7.9	0.74
IMC ($T_f = 0.4$)	45°	10.8	0.6
IMC ($T_f = 0.8$)	53°	12.8	0.5
IMC ($T_f = 1.2$)	59°	14.4	0.42

For system: $G(s) = \dfrac{1}{(1+s)^3}$ approximated as: $G_a(s) = \dfrac{e^{-0.8s}}{1+3.7s}$

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Note that: The IMC method produces more moderate control systems w.r.t. those obtained via the Cohen-Coon Method

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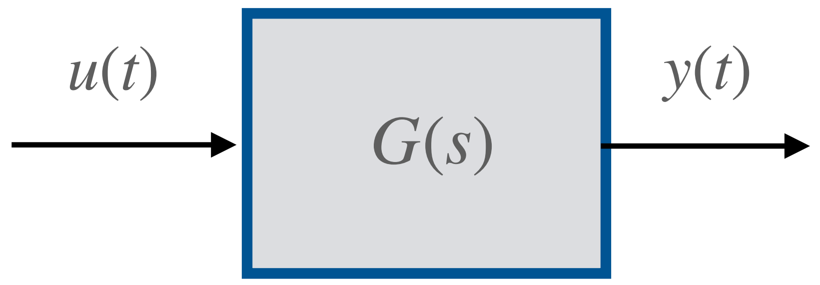
Exercise:
Determine the Control Sensitivity Functions for a PI tuned using Cohen-Coon or the IMC in the table for the considered $G(s)$

Note that: The IMC method produces more moderate control systems w.r.t. those obtained via the Cohen-Coon Method

PID Controllers: Wind-up Effect

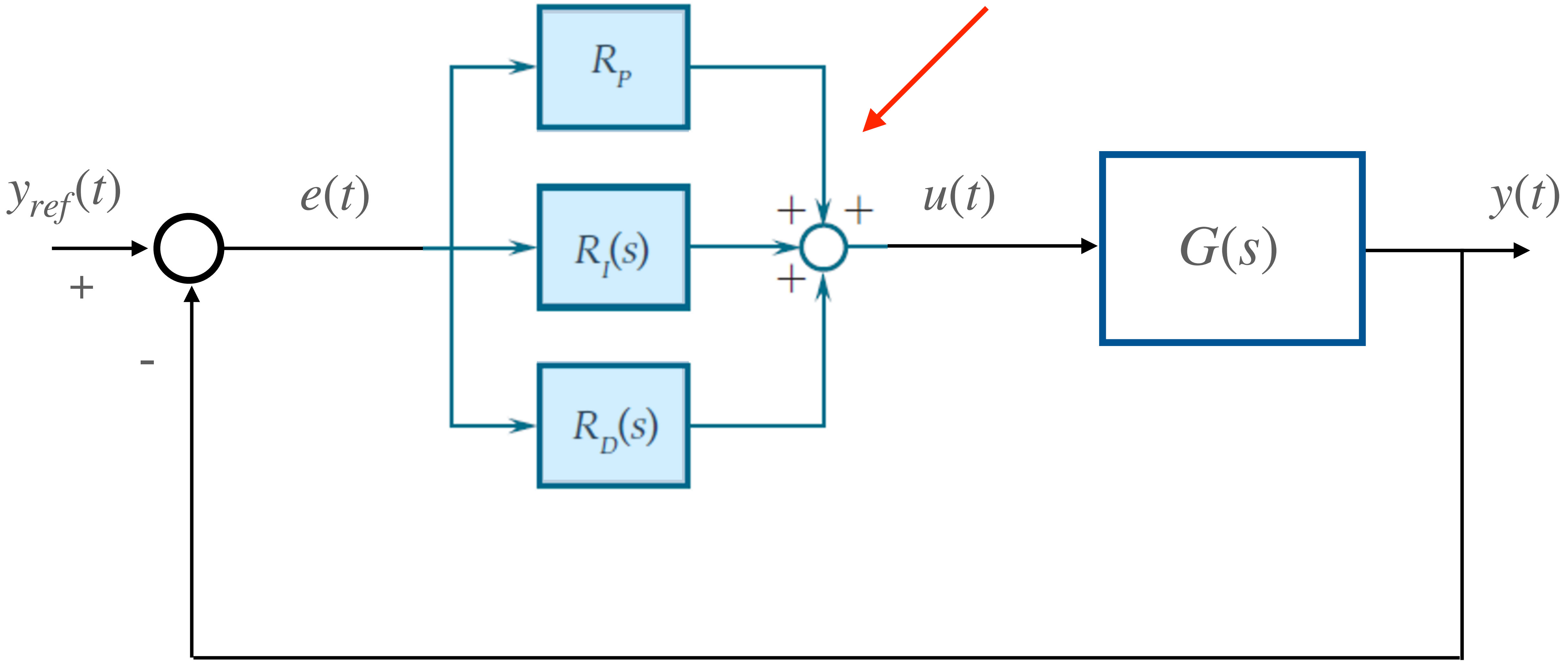
Process



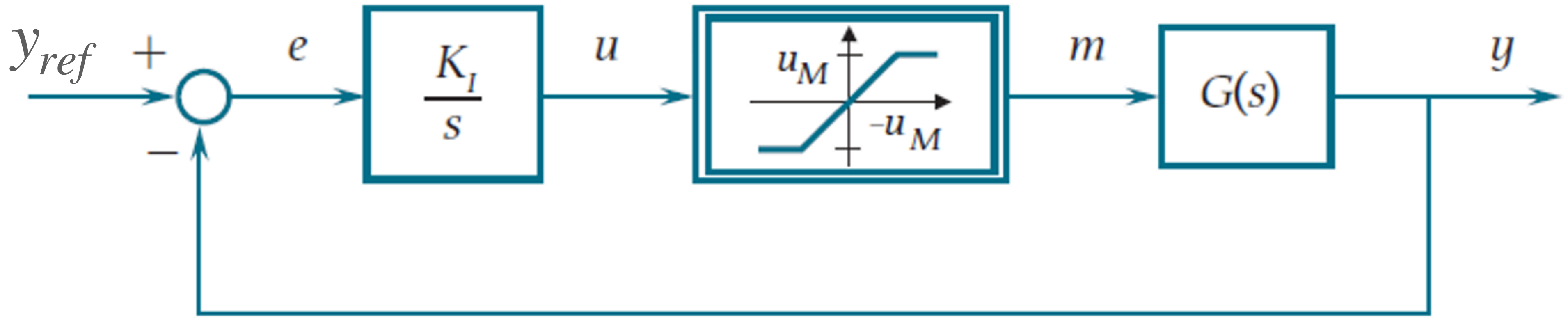
$u(t) \in \mathbb{R}$

$y(t) \in \mathbb{R}$

PID Controller



Realistic situation



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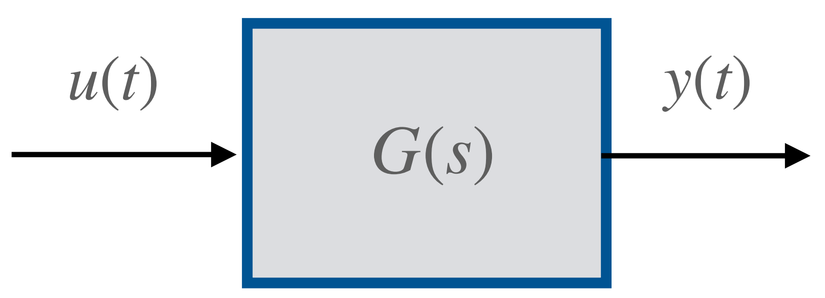

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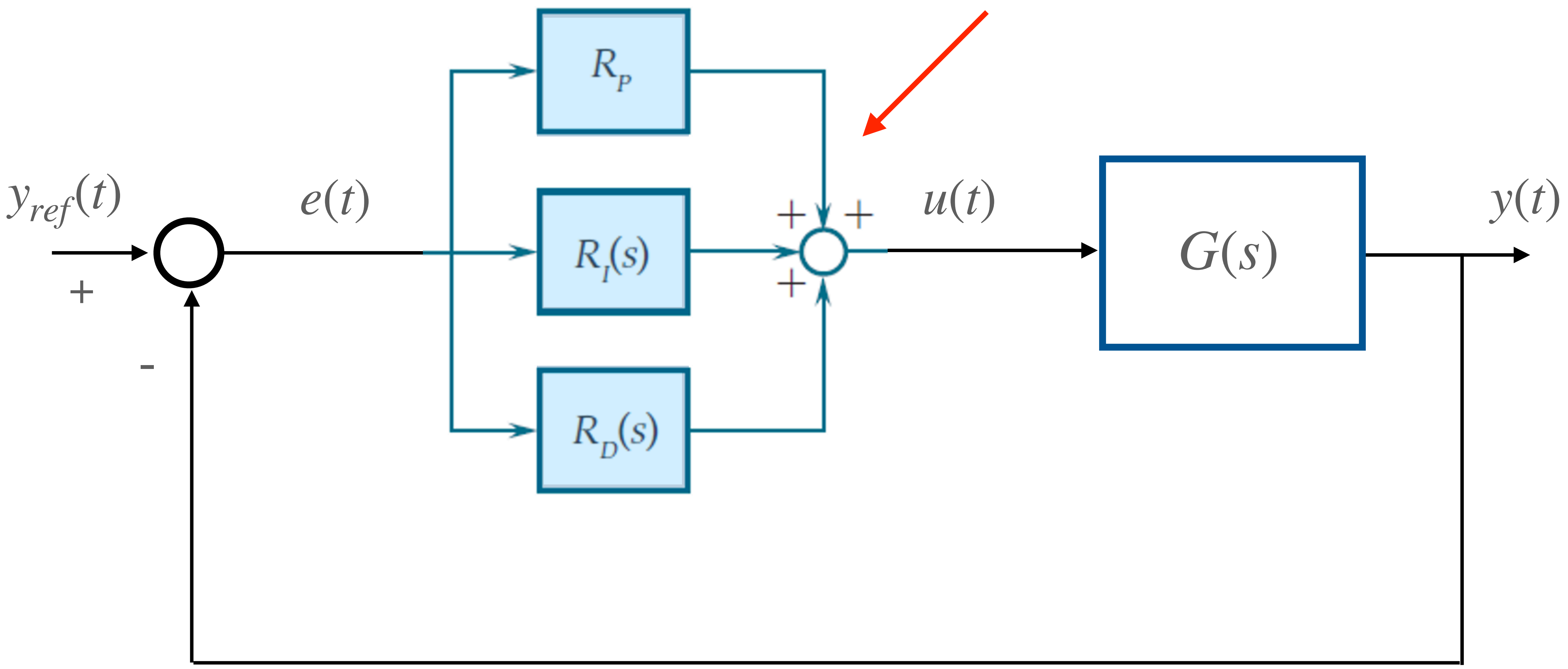

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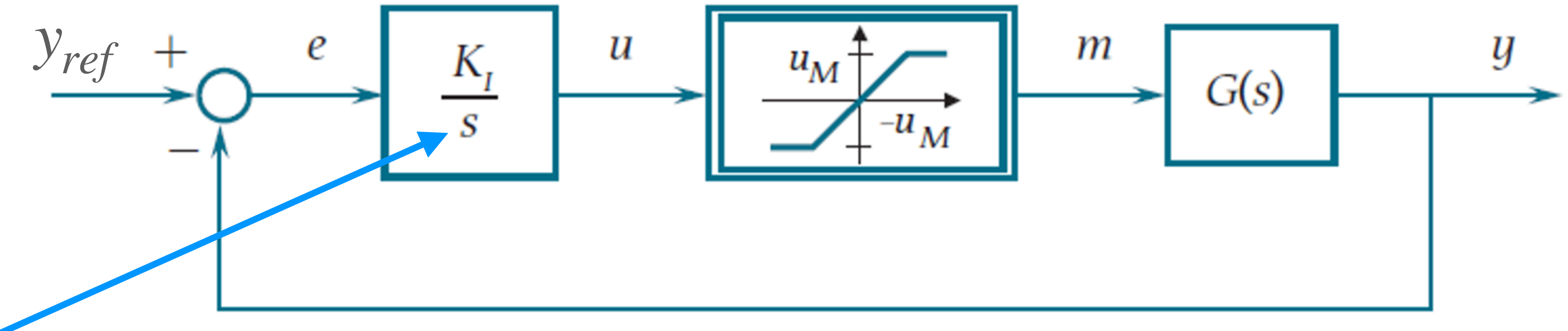
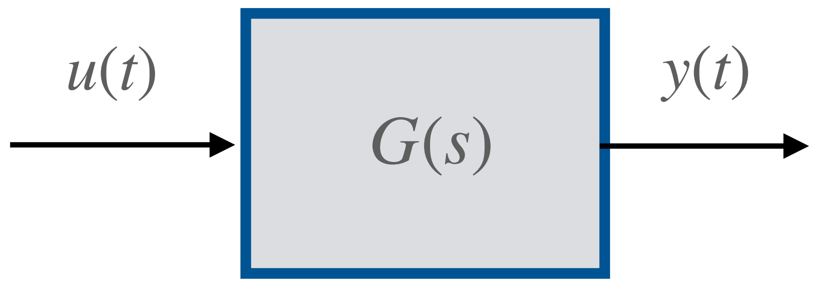


Only the integral component is considered

PID Controllers: Wind-up Effect

Process



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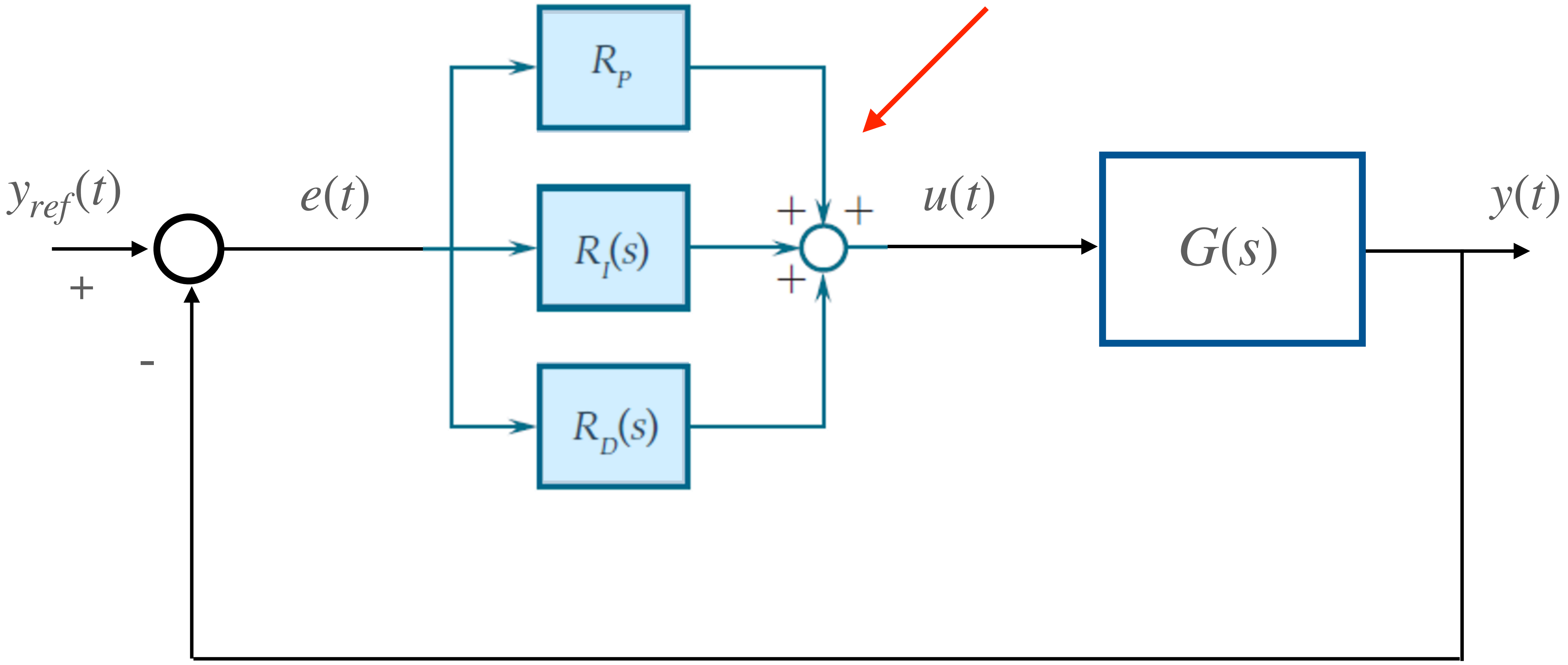
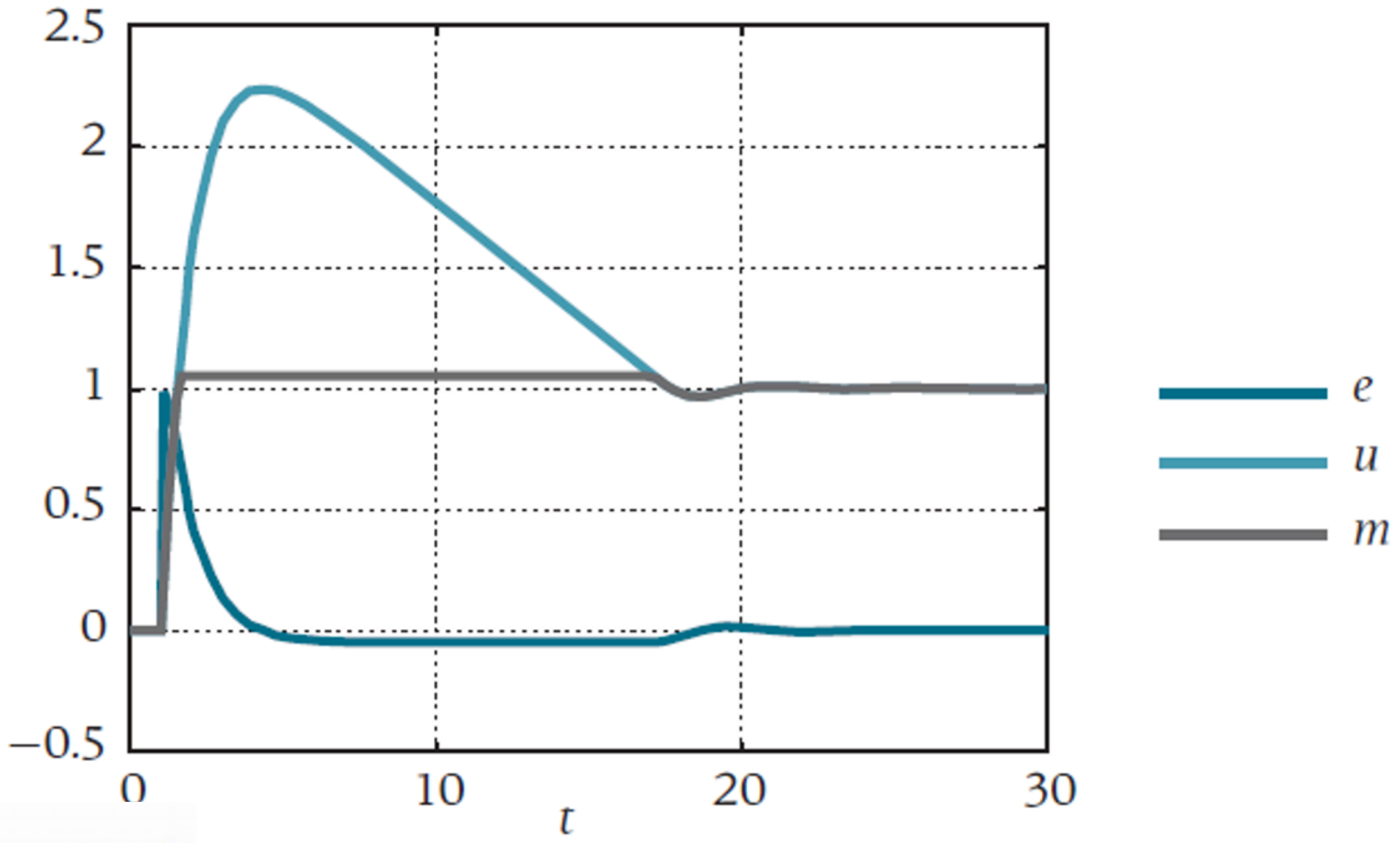
PID Controller





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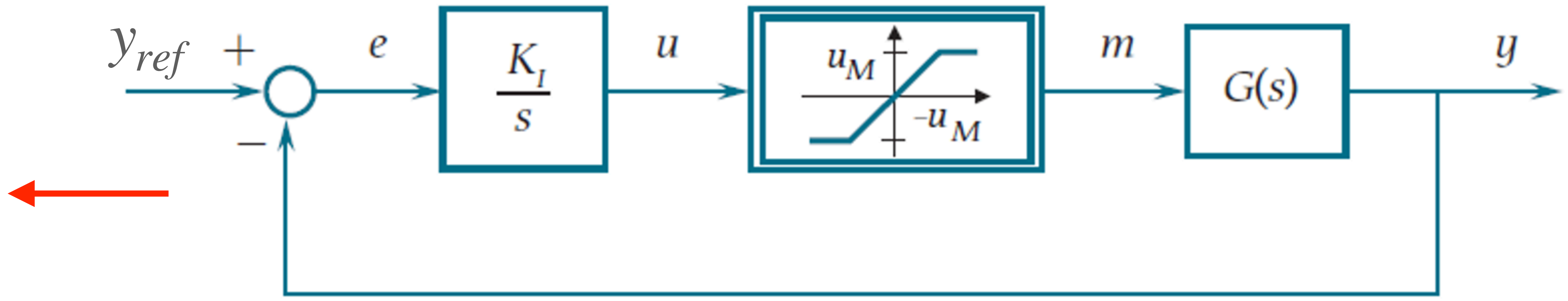

PID Controllers: Wind-up Effect

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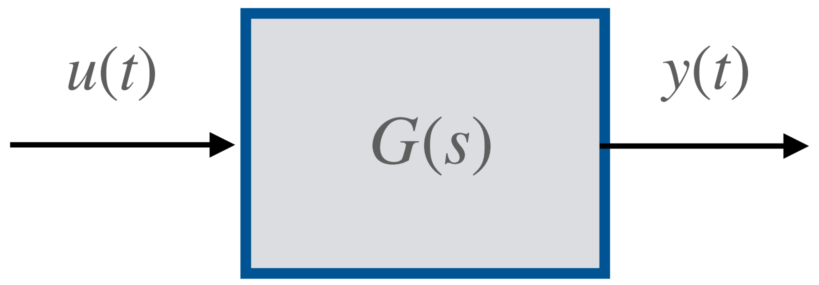

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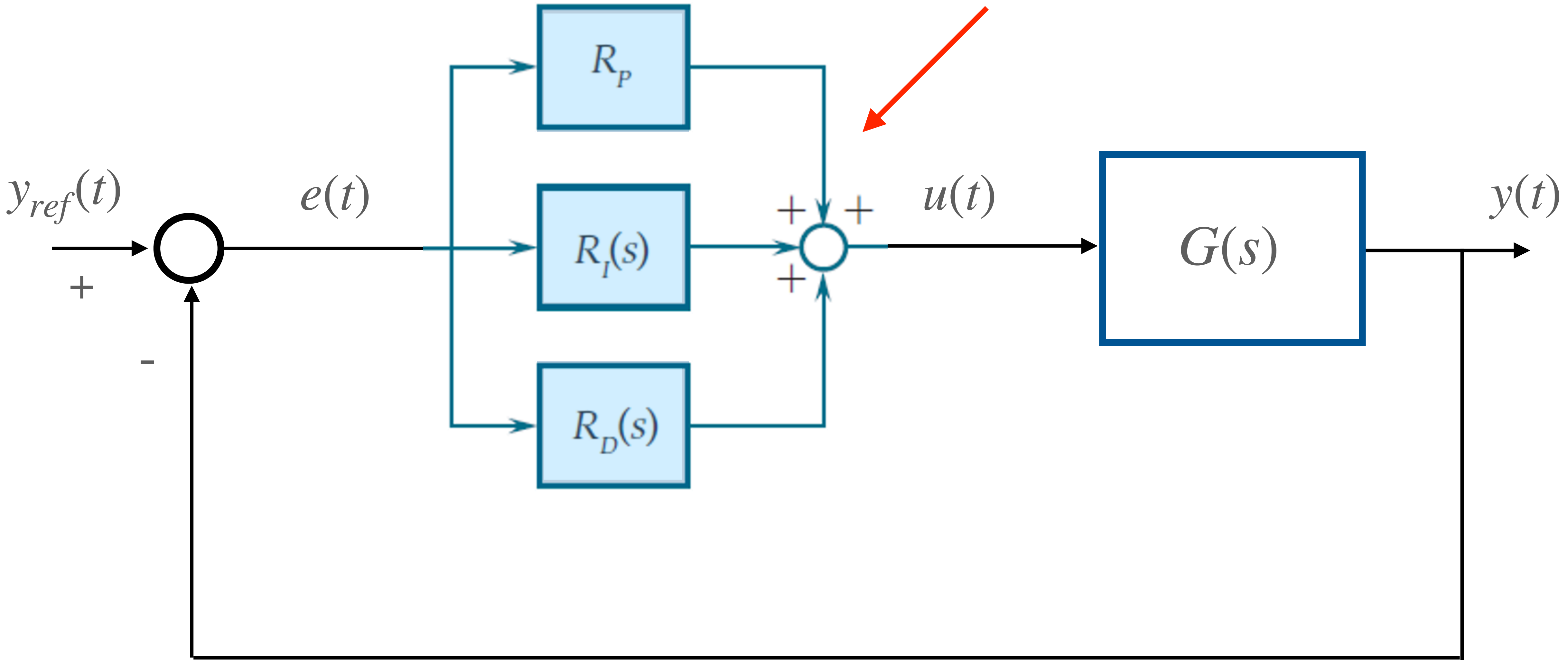

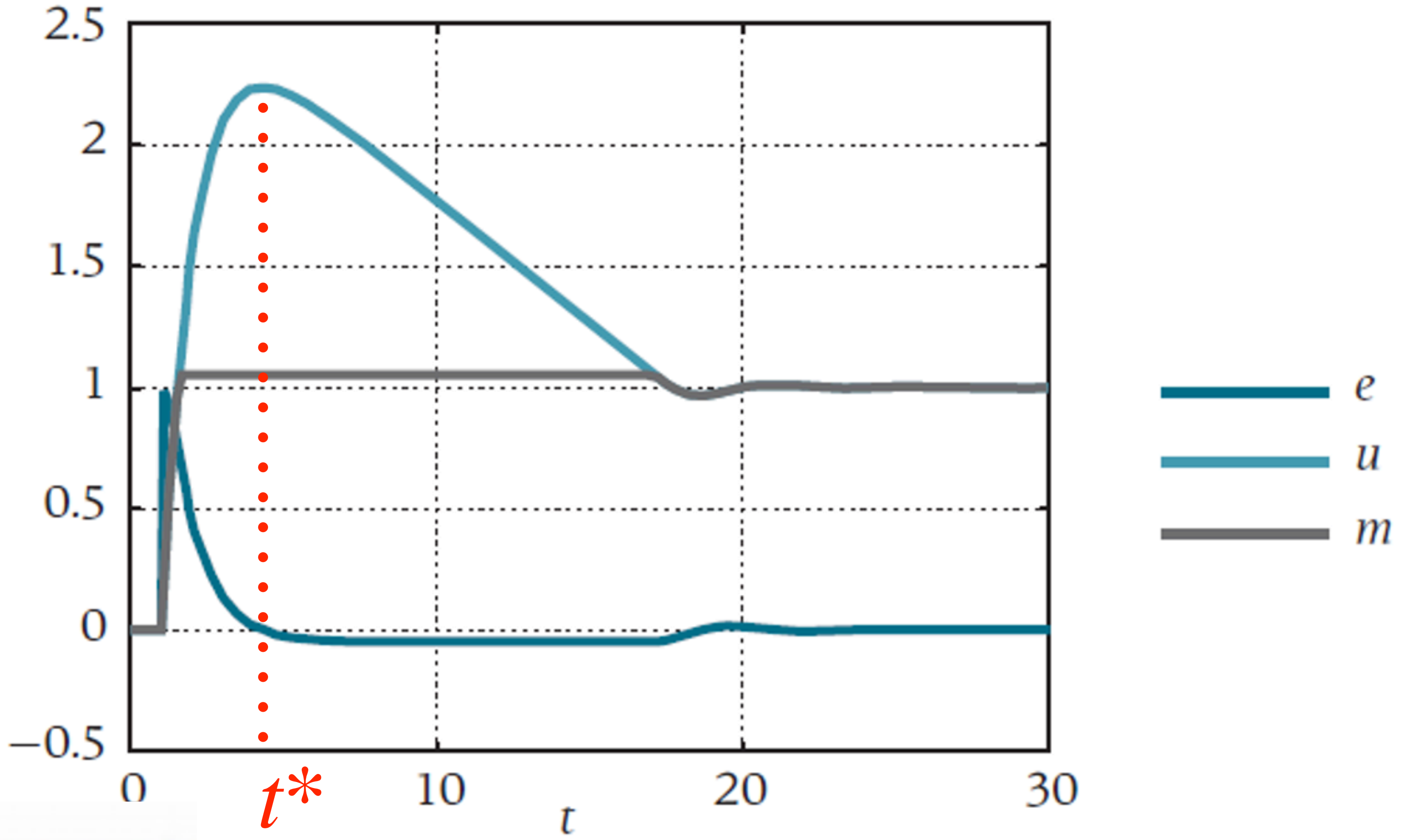

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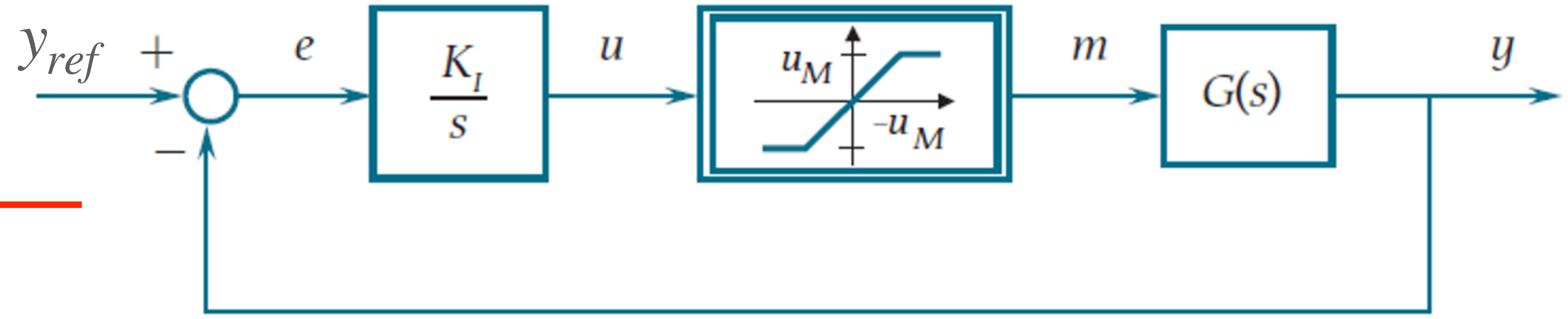
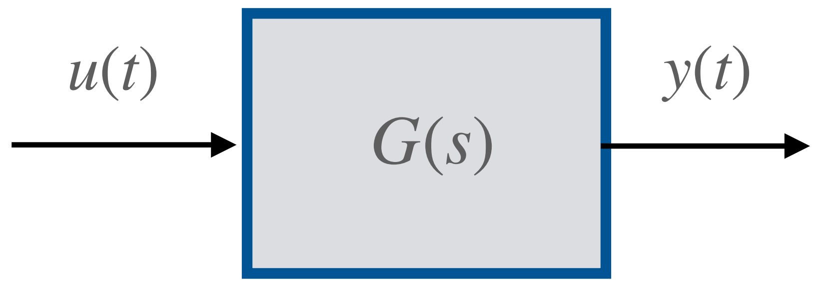


PID Controllers: Wind-up Effect

Process



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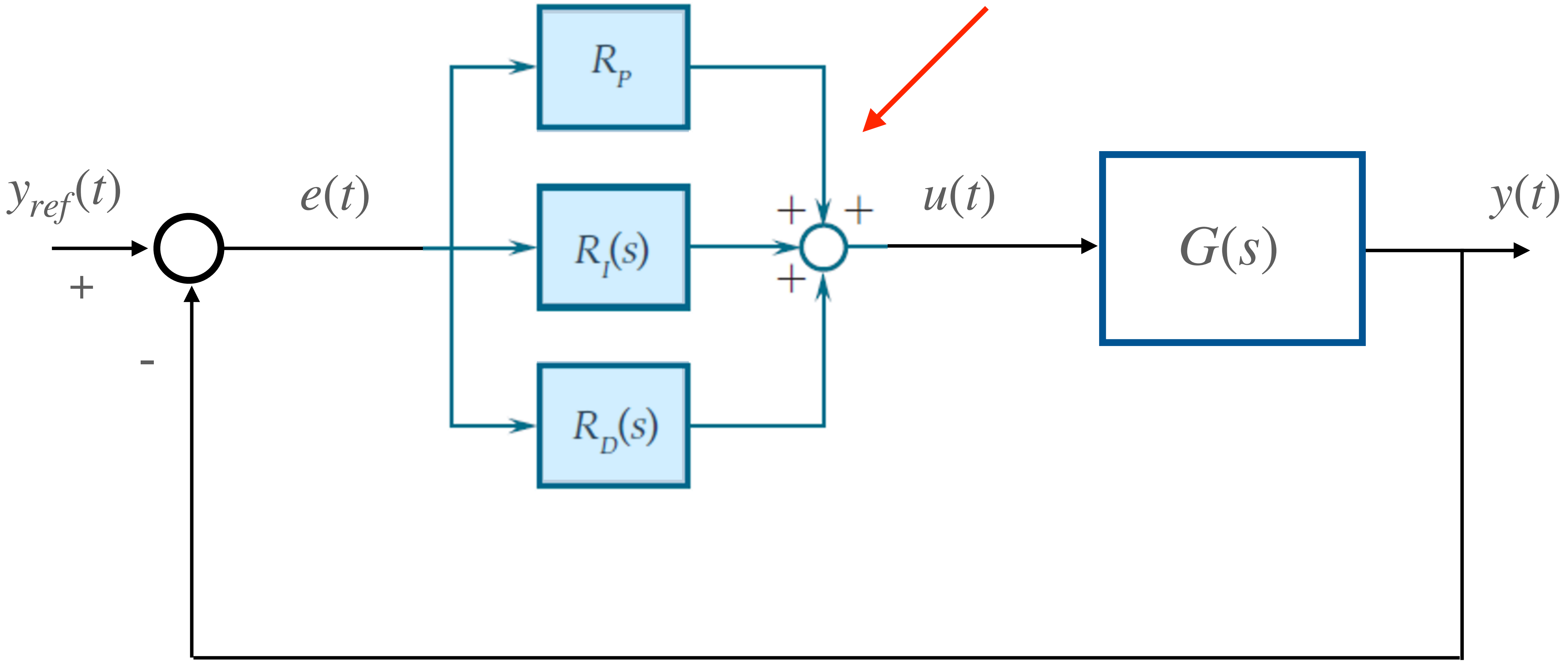
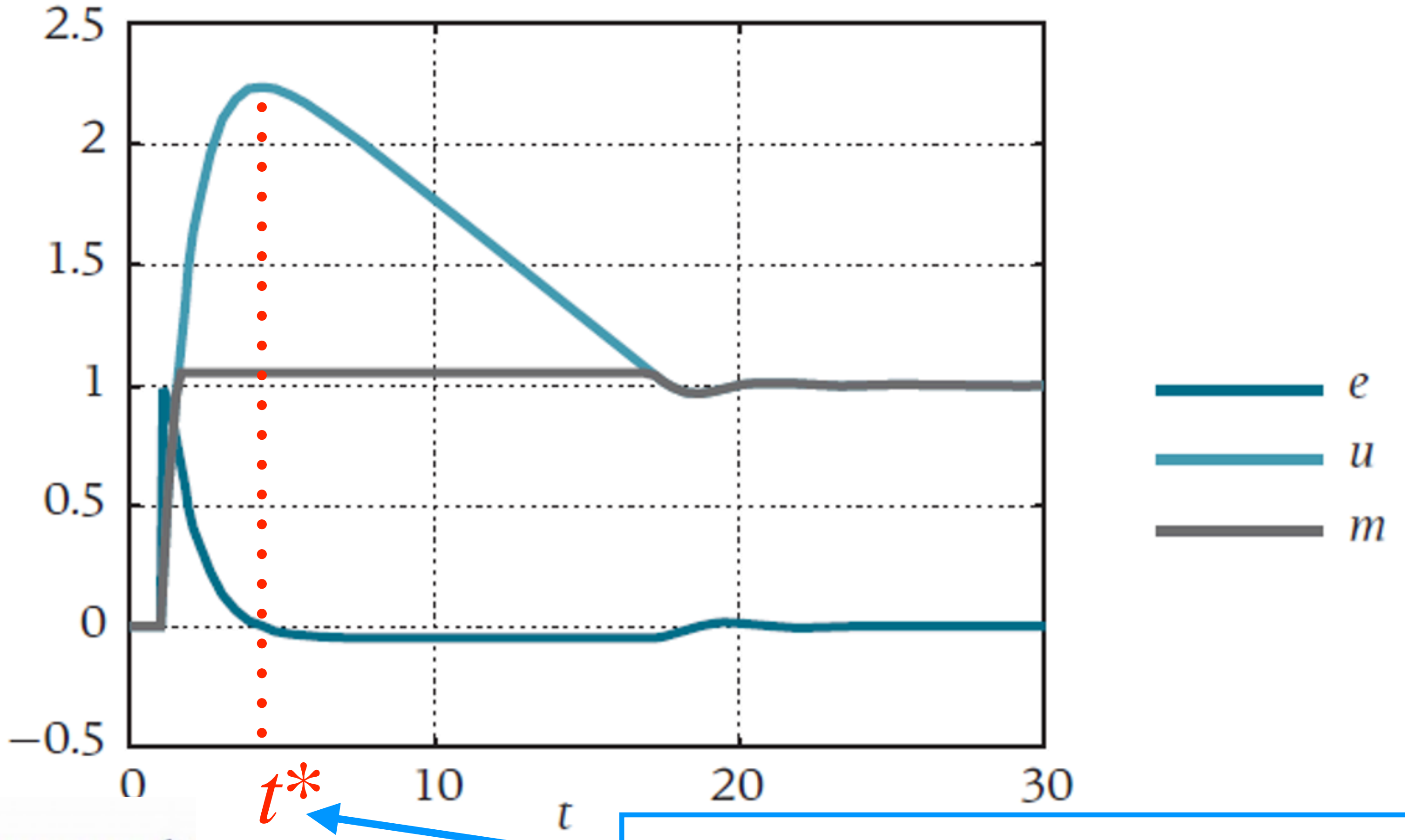
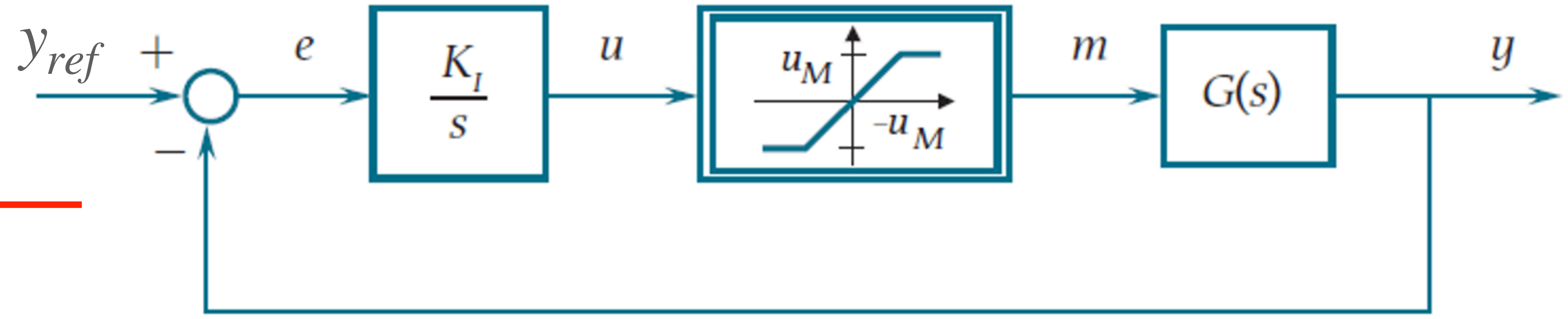
PID Controller





t^*

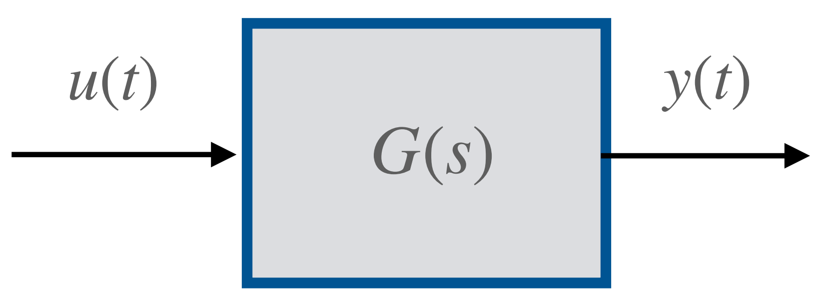
Realistic situation



Ideal situation: the control action exits the saturation mode when e starts decreasing (no useless waiting time due to wind-up)

PID Controllers: Wind-up Effect

Process



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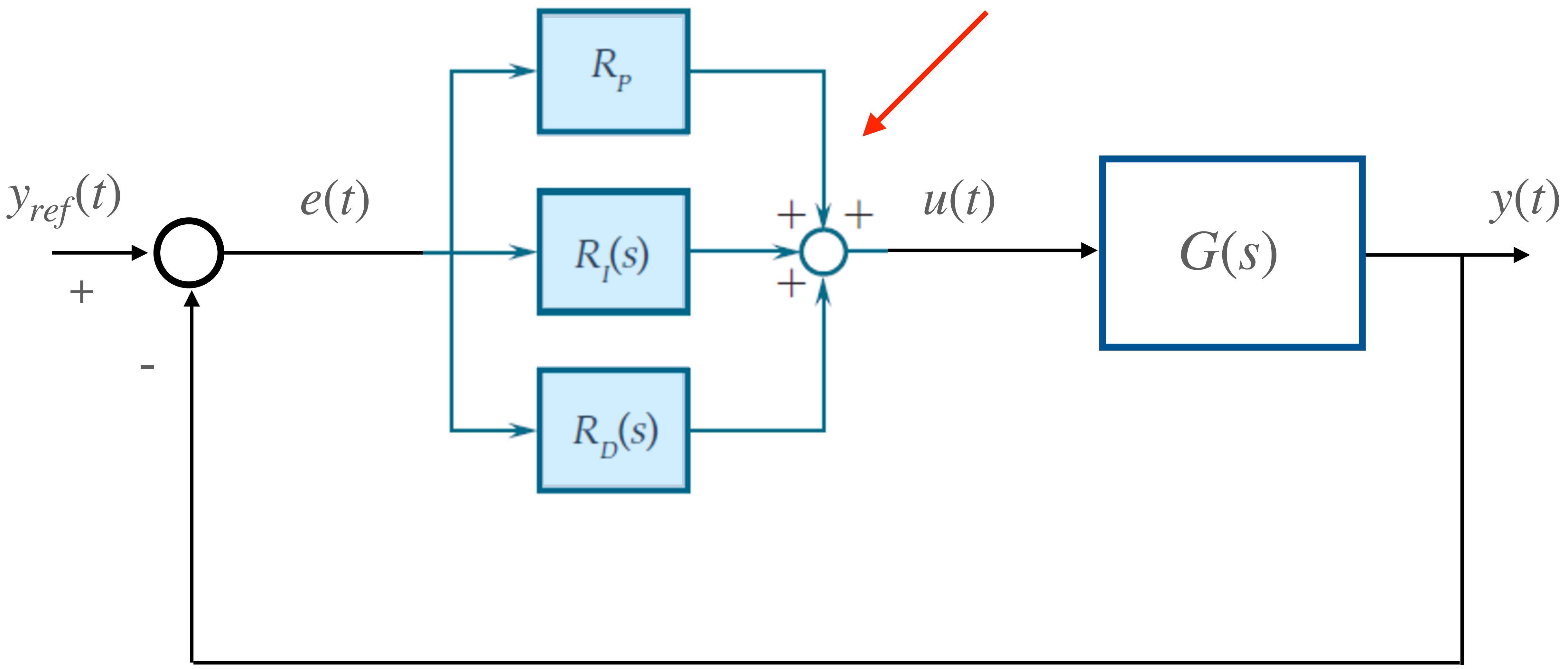
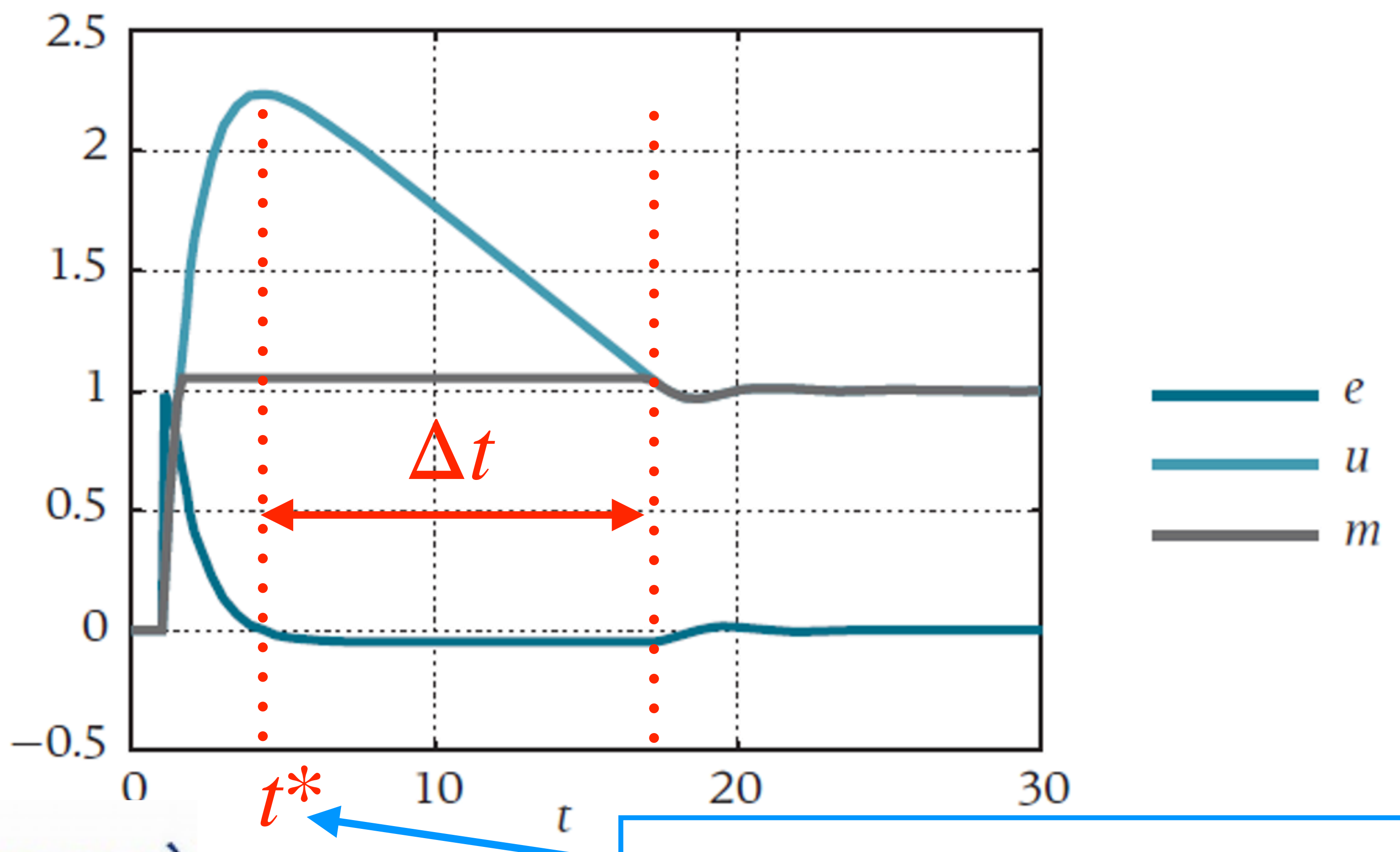
PID Controller





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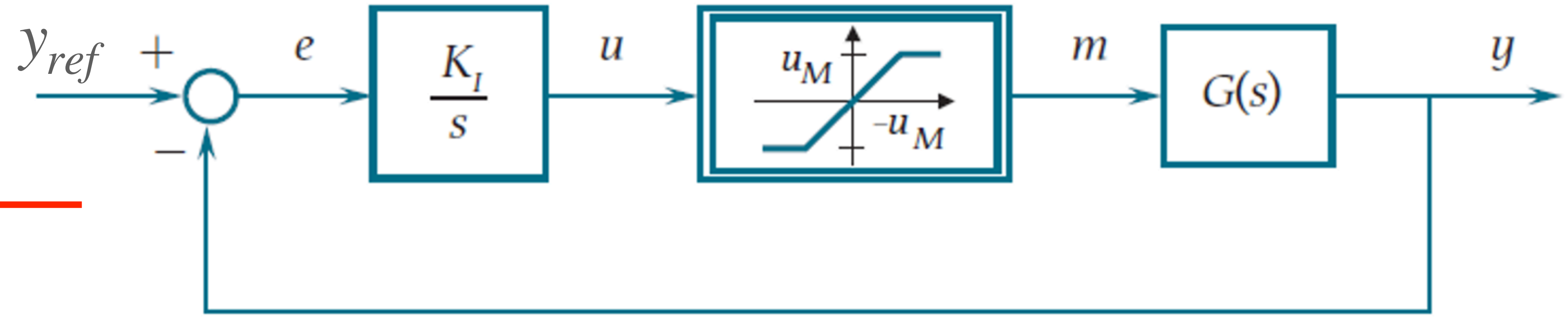

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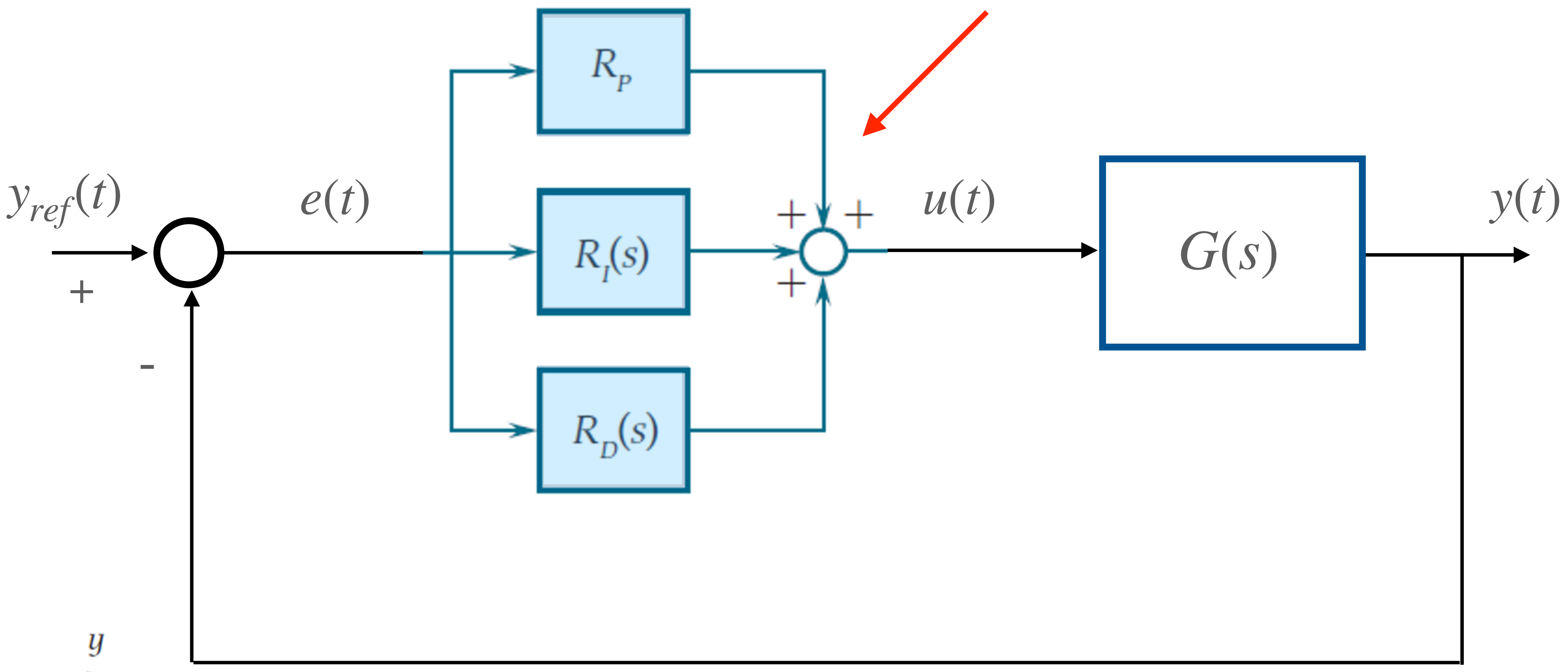
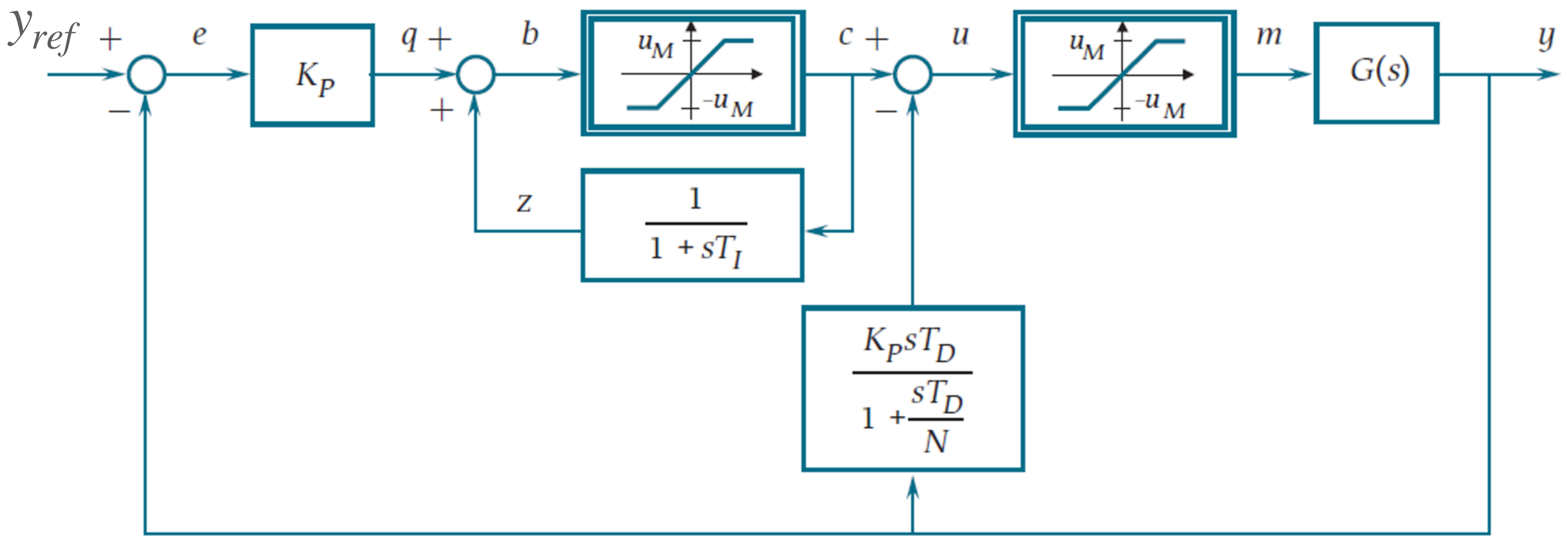
PID Controller



Solution: Anti-wind-up scheme



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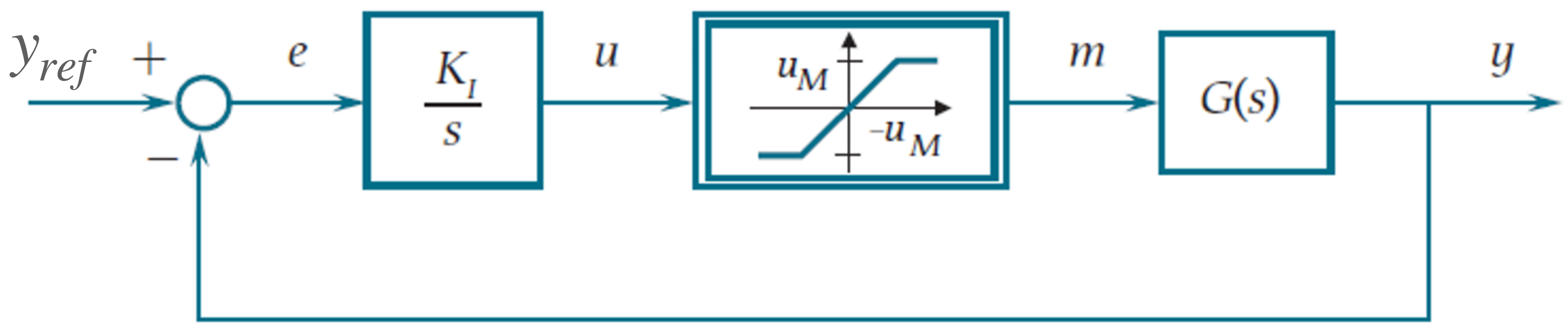
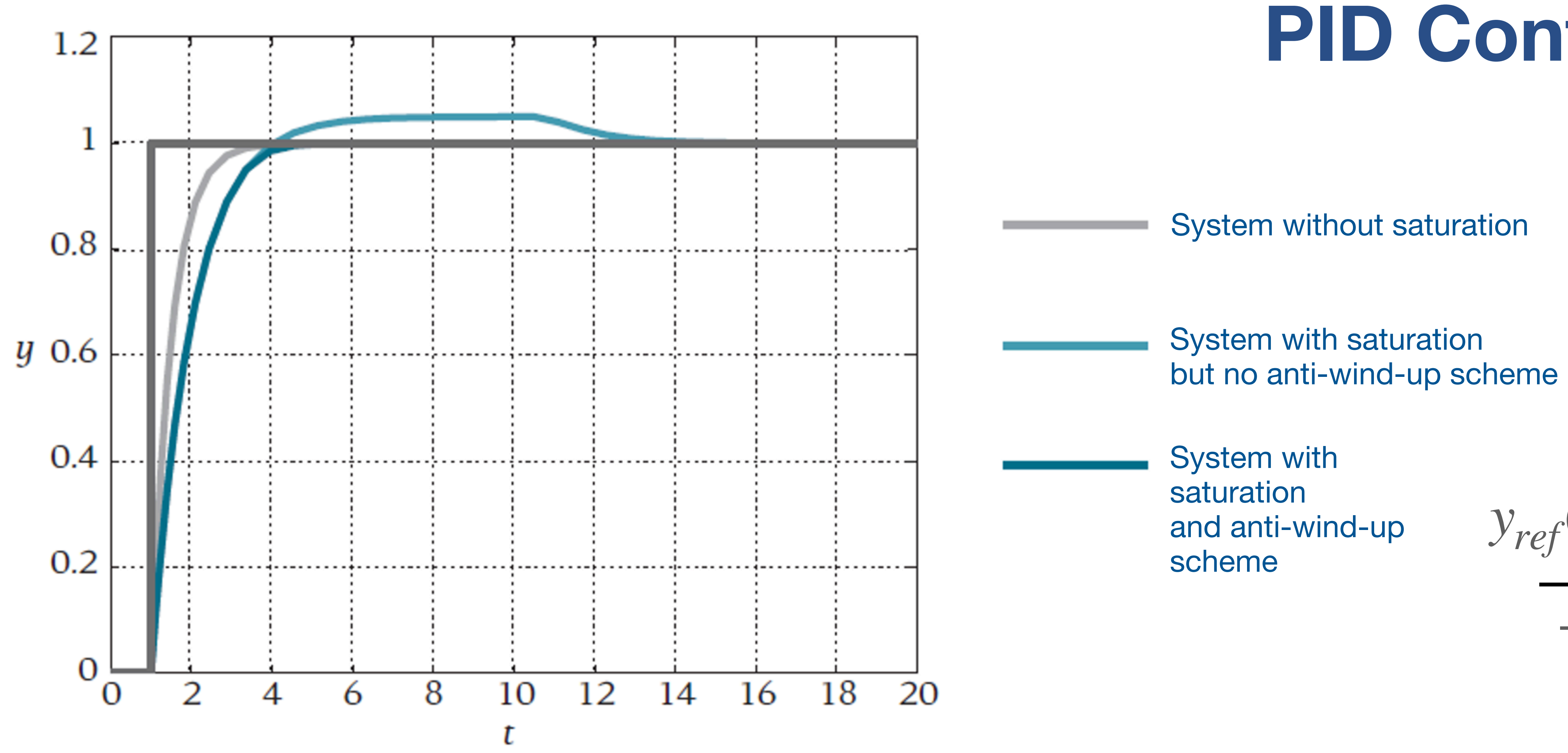
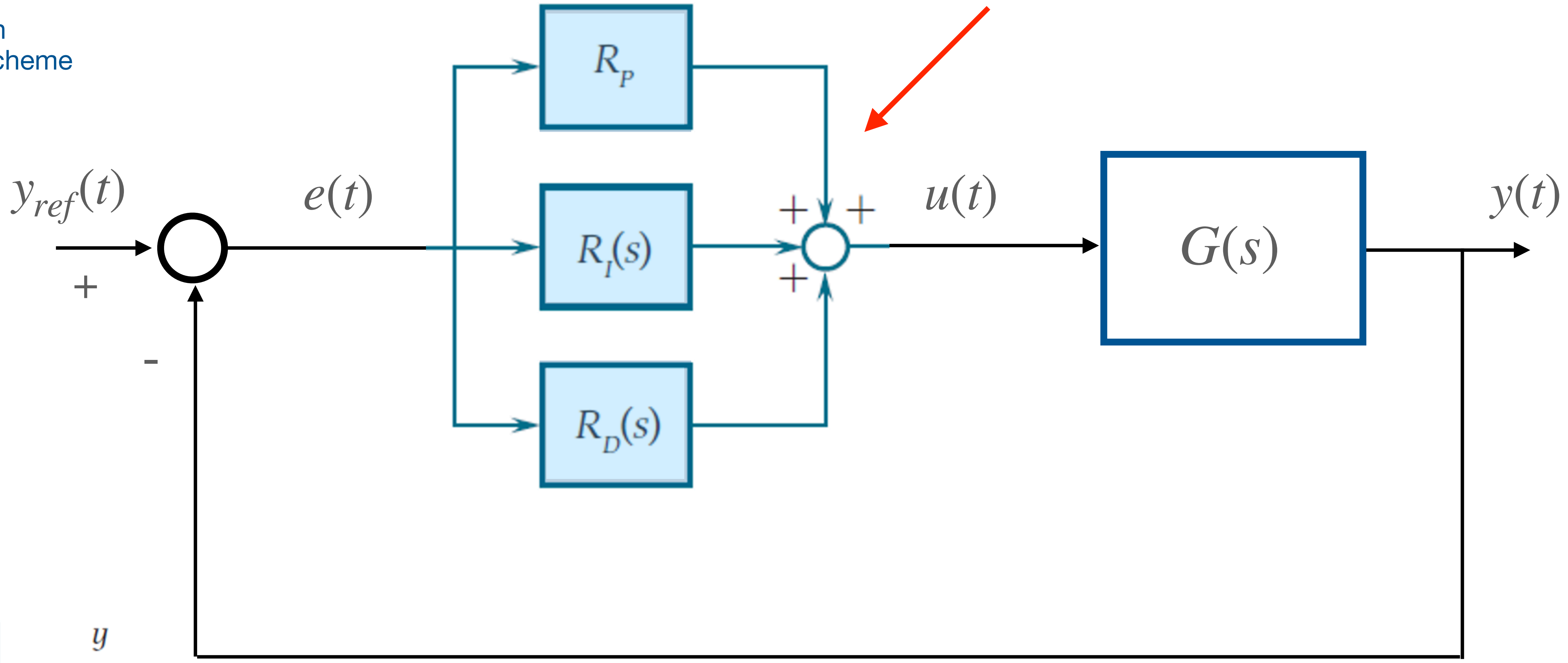


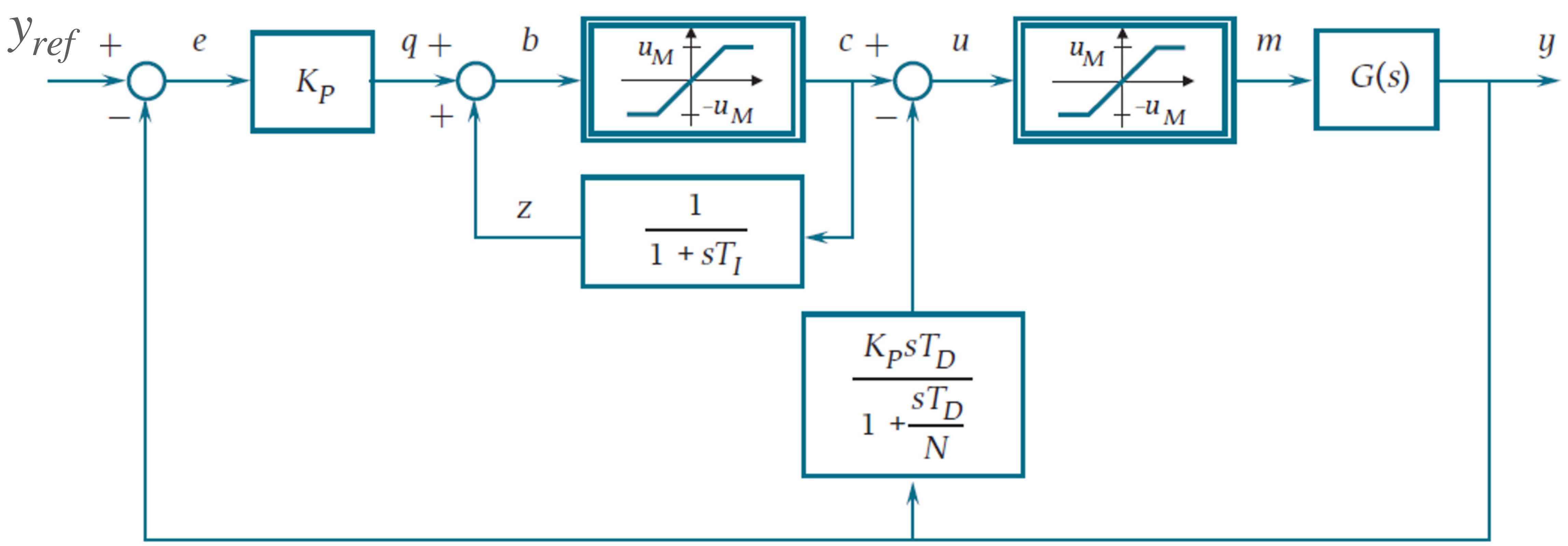
PID Controllers: Wind-up Effect



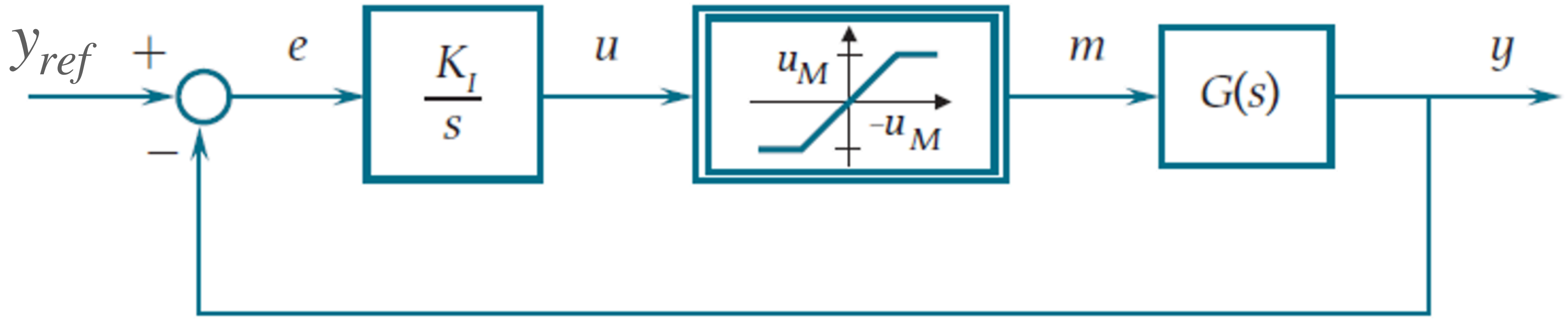
PID Controller



Solution: Anti-wind-up scheme



Realistic situation

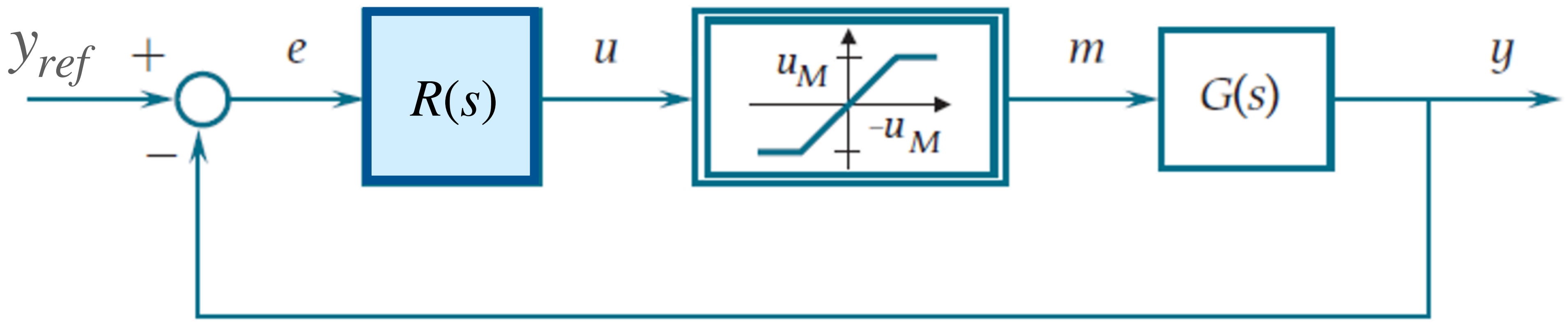


PID Controllers: Wind-up Effect

Generic integral controller

$$R(s) = \frac{N_R(s)}{D_R(s)}, \quad D_R(0) = 0$$

Realistic situation

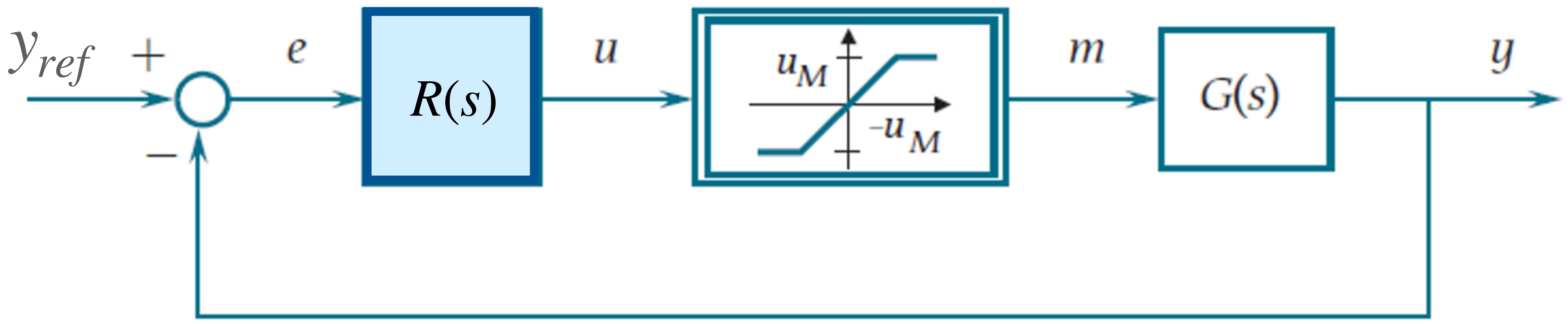


PID Controllers: Wind-up Effect

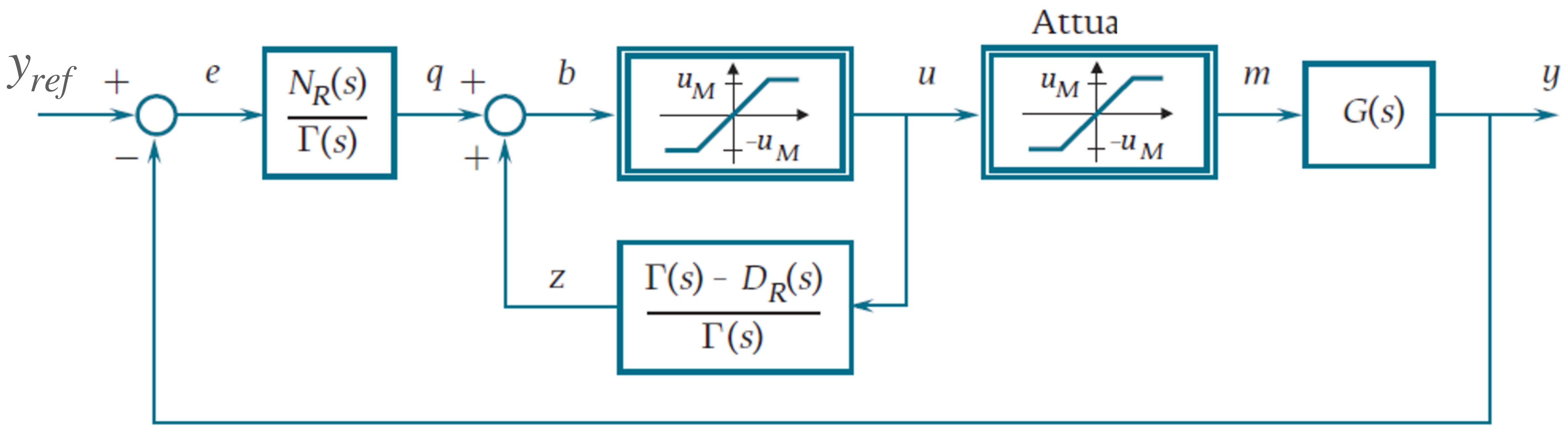
Generic integral controller

$$R(s) = \frac{N_R(s)}{D_R(s)}, \quad D_R(0) = 0$$

Realistic situation



Solution: Anti-wind-up scheme for generic integral controller

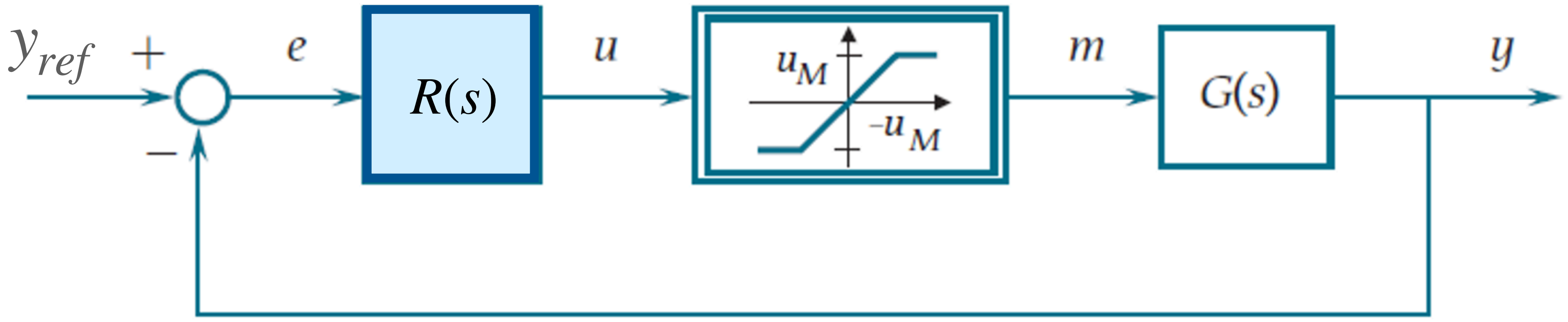


PID Controllers: Wind-up Effect

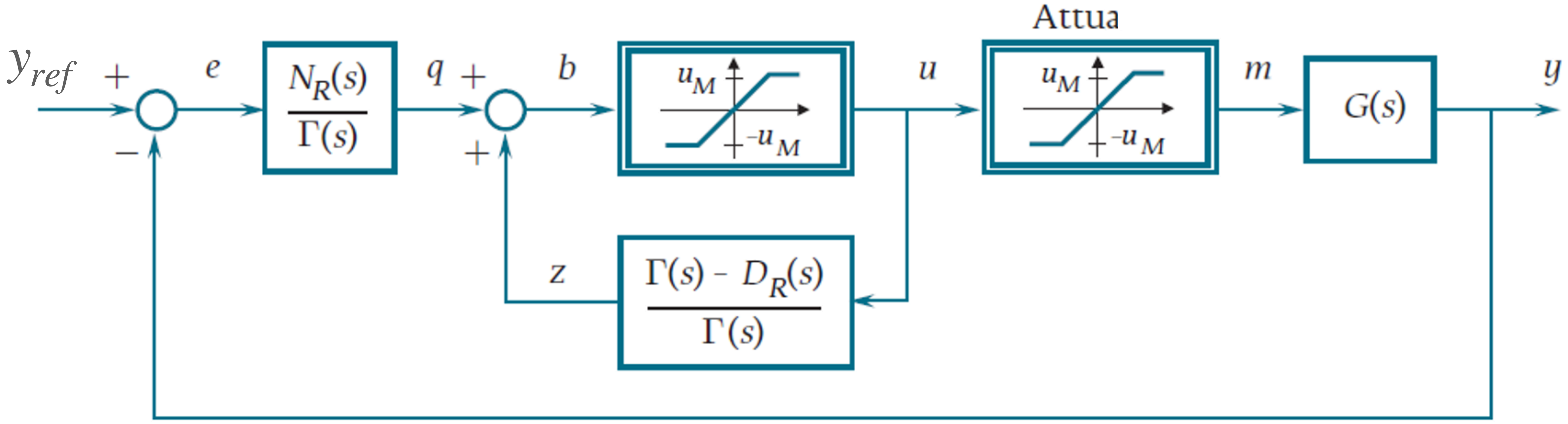
Generic integral controller

$$R(s) = \frac{N_R(s)}{D_R(s)}, \quad D_R(0) = 0$$

Realistic situation



Solution: Anti-wind-up scheme for generic integral controller



Alternative (accessible signal downstream of saturation)