Information Theory + Review & Applications

ELEC 3004: **Digital Linear Systems**: Signals & Controls

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Lecture 13

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Lecture Schedule:

Week	Date	Lecture Title
1	4-Mar	Introduction & Systems Overview
	6-Mar	[Linear Dynamical Systems]
2	11-Mar	Signals as Vectors & Systems as Maps
	13-Mar	[Signals]
3	18-Mar	Sampling & Data Acquisition & Antialiasing Filters
	20-Mar	[Sampling]
4	25-Mar	System Analysis & Convolution
	27-Mar	[Convolution & FT]
5	1-Apr	Frequency Response & Filter Analysis
	3-Apr	[Filters]
6	8-Apr	Discrete Systems & Z-Transforms
	10-Apr	[Z-Transforms]
7	15-Apr	Introduction to Digital Control
	17-Apr	[Feedback]
8	29-Apr	Digital Filters
	1-May	[Digital Filters]
9	6-May	Digital Control Design
	8-May	[Digitial Control]
10	13-May	Stability of Digital Systems
	15-May	[Stability]
11	20-May	State-Space
	22-May	Controllability & Observability
12	27-May	PID Control & System Identification
	29-May	Digitial Control System Hardware
13	3-Jun	Applications in Industry & Information Theory & Communications
	5-Jun	Summary and Course Review

Lab 4

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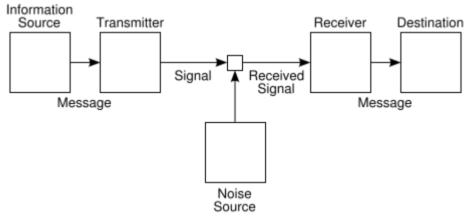
WARNING: NOT ASSESSABLE

- Nothing beyond this point is on the exam.
- Do not pay attention.
- Do not attempt to learn.

Shannon Information Theory



"The fundamental problem of communication is that of reproducing at one point, either exactly or approximately, a message selected at another point."

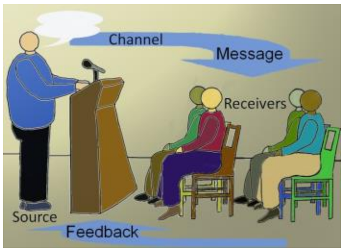
On the transmission of information over a noisy channel:

- An **information source** that produces a message
- A **transmitter** that operates on the message to create a signal which can be sent through a channel
- A **channel**, which is the medium over which the signal, carrying the information that composes the message, is sent
- A **receiver**, which transforms the signal back into the message intended for delivery
- A **destination**, which can be a person or a machine, for whom or which the message is intended

Shannon and Weaver: Models of Communication

Three "problems" in Communication:

- The technical problem: how accurately can the message be transmitted?
- The semantic problem: how precisely is the meaning "conveyed"?
- The effectiveness problem: how effectively does the received meaning affect behaviour?



Source: http://en.wikipedia.org/wiki/File:Transactional_comm_model.jpg

Additional Use of State-Space: Estimation

Along multiple dimensions

State Space

- We collect our set of uncertain variables into a vector …
  $\mathbf{x} = [x_1, x_2, \ldots, x_N]^T$
- The set of values that $\mathbf{x}$ might take on is termed the *state space*
- There is a *single* true value for $\mathbf{x}$,
  but it is unknown

State Space Dynamics

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$
$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

$$H(s) = C(sI - A)^{-1}B$$

Measured versus True

- Measurement errors are inevitable
- So, add Noise to State...
  - State Dynamics becomes:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + w$$
$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} + v$$

- Can represent this as a "Normal" Distribution

$$\mathcal{N}(x; \mu, \sigma) = \frac{1}{\left(\sqrt{2\pi}\right)\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Recovering The Truth

- Numerous methods
- Termed "Estimation" because we are trying to estimate the truth from the signal
- A strategy discovered by Gauss
- Least Squares in Matrix Representation

$$\begin{bmatrix} p_0 \\ p_1 \end{bmatrix} = \begin{bmatrix} n & \sum_1^n t_i \\ \sum_1^n t_i & \sum_1^n t_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_1^n z_i \\ \sum_1^n t_i z_i \end{bmatrix}$$

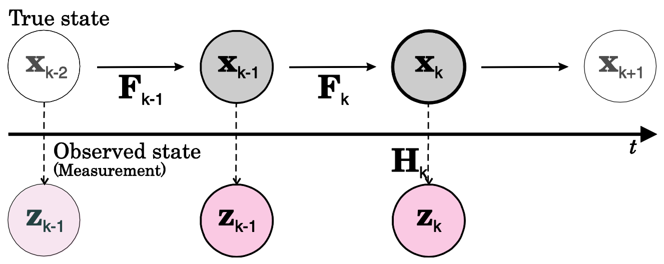
Recovering the Truth: Terminology

$$\dot{\mathbf{x}} = \mathbf{F}\mathbf{x} + \mathbf{G}\mathbf{u} + \mathbf{w}$$

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{v}$$

- $\mathbf{x}$: the state vector
- $\mathbf{x}_{A|B}$: the state of $\mathbf{x}$ at time A based on data taken up to time B
- $\hat{\mathbf{x}}$: estimate of the true state vector
- $\mathbf{F}$: system dynamics matrix in continuous time (equivalent to $\mathbf{A}$ in Eq. 1)
- $\mathbf{G}$: system control matrix relating deterministic input, $\mathbf{u}$, to the state (equivalent to $\mathbf{B}$ in Eq. 1)
- $\mathbf{H}$: measurement matrix in continuous time (equivalent to $\mathbf{C}$ in Eq. 2)
- $\mathbf{F}_i$: system model in **discrete** time at $t = t_i$
- $\mathbf{H}_i$: measurement model in **discrete** time at $t = t_i$
- $\mathbf{P}_i$: estimate covariance in **discrete** time at $t = t_i$
- $\mathbf{w}$: process uncertainty (noise) vector (of type $\mathcal{N}(0, s)$)
- $\mathbf{Q}$: process noise matrix, $\mathbf{Q} = E\left[ww^{\mathsf{T}}\right]$
- $\mathbf{Q}_i$: $\mathbf{Q}$ in discrete time at $t = t_i$
- $\mathbf{v}$: measurement noise vectors (of type $\mathcal{N}(0, \sigma)$)
- $\mathbf{R}_i$: the measurement variance matrix, $\mathbf{R} = E\left[vv^{\mathsf{T}}\right]$, in discrete time at $t = t_i$

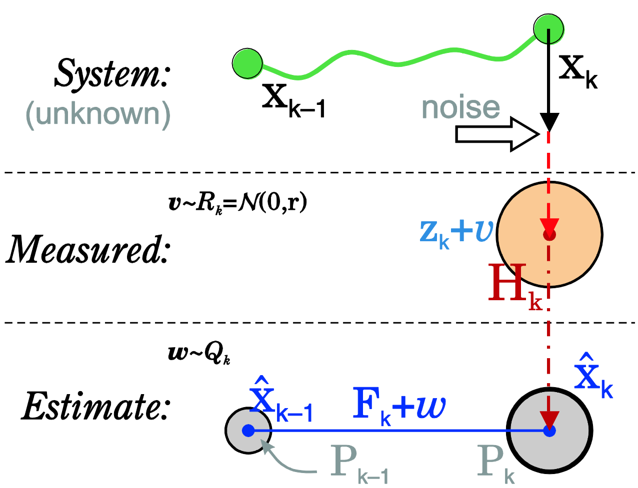
General Problem…



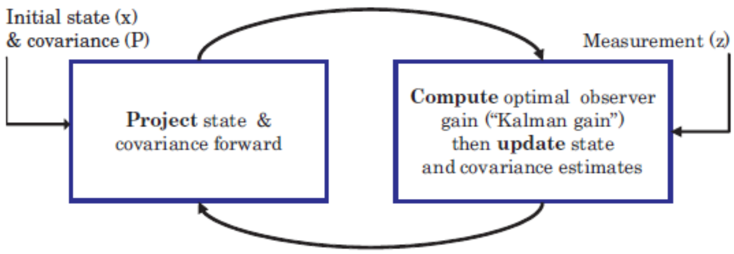
Duals and Dual Terminology

	Estimation		Control
Model:	$\dot{x} = Fx$ (discrete: $x = F_k x$)	$\leftrightarrow$	$\dot{x} = Ax$, $A = F^T$
Regulates:	P (covariance)	$\leftrightarrow$	M (performance matrix)
Minimized function:	Q (or GQG^T)	$\leftrightarrow$	V
Optimal Gain:	K	$\leftrightarrow$	G
Completeness law:	Observability	$\leftrightarrow$	Controllability

Estimation Process in Pictures



Kalman Filter Process



KF Process in Equations

$$
\begin{aligned}
\text{Prediction: } & \hat{\mathbf{x}}_{k|k-1} = \mathbf{F}_{k-1}\hat{\mathbf{x}}_{k-1|k-1}, && \text{(state prediction)} \\
& \mathbf{P}_{k|k-1} = \mathbf{Q}_{k-1} + \mathbf{F}_{k-1}\mathbf{P}_{k-1|k-1}\mathbf{F}^{\mathsf{T}}{}_{k-1}, && \text{(covariance prediction)} \\
\text{Kalman Gain: } & \mathbf{K}_k = \mathbf{P}_{k|k-1}\mathbf{H}^{\mathsf{T}}[\mathbf{H}\mathbf{P}_{k|k-1}\mathbf{H}^{\mathsf{T}} + \mathbf{R}_k]^{-1}, \\
\text{Update: } & \mathbf{P}_{k|k} = [\mathbf{I} - \mathbf{K}_k\mathbf{H}]\mathbf{P}_{k|k-1}, && \text{(covariance update)} \\
& \hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k(\mathbf{z}_k - \mathbf{H}\hat{\mathbf{x}}_{k|k-1}) && \text{(state update)}
\end{aligned}
$$

KF Considerations

$$
\begin{aligned}
\underbrace{\hat{\mathbf{x}}_{k|k-1}}_{n\times 1} &= \underbrace{\mathbf{F}_{k-1}}_{n\times n}\hat{\mathbf{x}}_{k-1|k-1} + \underbrace{\mathbf{G}_{k-1}}_{n\times j}\underbrace{\mathbf{u}_{k-1}}_{j\times 1} \\
\underbrace{\mathbf{P}_{k|k-1}}_{n\times n} &= \underbrace{\mathbf{Q}_{k-1}}_{n\times n} + \mathbf{F}_{k-1}\mathbf{P}_{k-1|k-1}\mathbf{F}^{\mathsf{T}}{}_{k-1} \\
\underbrace{\mathbf{K}_k}_{n\times m} &= \mathbf{P}_{k|k-1}\underbrace{\mathbf{H}^{\mathsf{T}}}_{n\times m}\underbrace{\left[\mathbf{H}\mathbf{P}_{k|k-1}\mathbf{H}^{\mathsf{T}} + \mathbf{R}_k\right]^{-1}}_{m\times m} \\
\mathbf{P}_{k|k} &= [\mathbf{I} - \mathbf{K}_k\mathbf{H}]\mathbf{P}_{k|k-1} \\
\hat{\mathbf{x}}_{k|k} &= \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k(\underbrace{\mathbf{z}_k}_{m\times 1} - \underbrace{\mathbf{H}}_{m\times n}\hat{\mathbf{x}}_{k|k-1} - \mathbf{H}\mathbf{G}_k\mathbf{u}_{k-1})
\end{aligned}
$$

Ex: Kinematic KF: Tracking

- Consider a System with Constant Acceleration

$$
\begin{aligned}
\ddot{y} &= -g \\
\dot{y} &= gt + p_1 \\
y &= p_0 + p_1 t + \frac{gt^2}{2}
\end{aligned}
$$

$$
\begin{bmatrix} \dot{y} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} y \\ \dot{y} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} 0 \\ g \end{bmatrix}
$$

$$
\mathbf{F} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad \mathbf{F_k} = \begin{bmatrix} 0 & t_s & \frac{t_s{}^2}{2} \\ 0 & 0 & t_s \\ 0 & 0 & 0 \end{bmatrix}
$$

$$
\hat{\mathbf{x}}_k = \mathbf{F}_{k-1}\hat{\mathbf{x}}_{k-1} + \mathbf{K}_k(\mathbf{z}_k - \mathbf{H}\mathbf{F}_{k-1}\hat{\mathbf{x}}_{k-1})
$$

In Summary

- KF:
  - The true state (*x*) is separate from the measured (*z*)
  - Lets you **combine** prior controls knowledge with measurements to filter signals and find the truth
  - It **regulates** the covariance (P)
    - As P is the scatter between *z* and *x*
    - So, if P → 0, then *z* → *x* (measurements → truth)
- EKF:
  - Takes a Taylor series approximation to get a local "F" (and "G" and "H")

ELEC 3004: A Review

AKA ELEC 3004: **What do I need to know about *.* ???**

To Review: Back to the **Beginning…Lecture 1 Slide 9**

- Systems
- Signal Abstractions
- Signals as Vectors / Systems as Maps

- Linear Systems and Their Properties
- LTI Systems
- Autonomous Linear Dynamical Systems

- Convolution
- FIR & IIR Systems
- Frequency domain
- Fourier Transform (CT)
- Fourier Transform (DT)

- Even and Odd Signals
- Likelihood
- Causality

- Impulse Response
- Root Locus
- Bode Functions

- Left-hand Plane

- Frequency Response

- Discrete Time
- Continuous Time

- Laplace Transformation
- Feedback and Control
- Additional Applications

- Linear Functions
- Linear Algebra Review
- Least Squares
- Least Squares Problems
- Least Squares Applications
- Matrix Decomposition and Linear Algebra
- Regularized Least Squares

- Least-squares
- Least-squares applications
- Orthonormal sets of vectors
- Eigenvectors and diagonalization
- Linear dynamical systems with inputs and outputs
- Symmetric matrices, quadratic forms, matrix norm, and SVD

- Controllability and state transfer
- Observability and state estimation

- And that, of course,
  Linear Systems are Cool! ☺

Lots of Stuff To Cover…

- Systems
- Signal Abstractions
- Signals as Vectors / Systems as Maps

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Linear Systems are Cool! ☺

Review

- What do you think when you see?

$$\ddot{y} + 2\dot{y} + 3y = u$$

- System?
- ODE?
- Linear Algebra?
- Joy?
- Excitement?
- Shock and Awe??

Linear algebra provides the tools/foundation for working with (linear) differential equations.

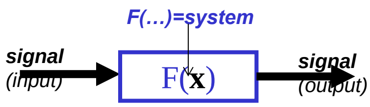
Linear algebra provides the tools/foundation for working with (linear) differential equations.

- Signals are vectors. Systems are matrices.

$$\mathbf{y} = F\mathbf{x} + G\mathbf{u}$$

Linear Systems

Linear Systems in 1-Slide



- Signals Are Vectors

- Systems Are Matricies

Is it Useful?

Yes.

(For example … Next Year – ELEC/METR 3800)

It Can Rock Your Boat Gently Down The Stream: IMU Deaduced Reckoning (Navigation)

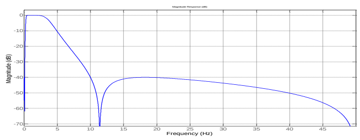
Idea: Integrate your motion (twice for $\ddot{x} \rightarrow x$ and once for $\dot{\theta} \rightarrow \theta$)

Problem:

- (DC) bias in accelerometer → drift

Solution:

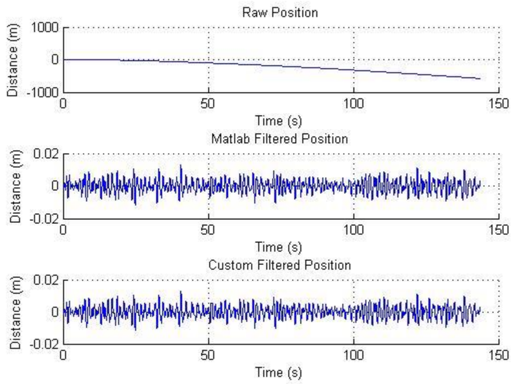
- IIR Bandpass filter (0.1-10 Hz)



```
A = [1.0000   -5.8235   14.1332  -18.2966   13.3259   -5.1772    0.8382];
B = [0.9155   -5.4933   13.7331  -18.3109   13.7331   -5.4933    0.9155];
```


It Can Rock Your Boat Gently Down The Stream: IMU Deaduced Reckoning (Navigation) [2]

Solution:



Extra Material:
(For Fun!)

Poles are Eigenvalues

The Direct Method
of Digital Controls –

NOT to be confused with
Controller Emulation
(e.g., Tustin's Method)

Direct Design Method Of Ragazzini (See also: FPW 5.7 pp.216-222)

Start with 3 Discrete Transfer Functions:

- **G(z)**: TF[1] of a **plant + a hold** (e.g., from a ZOH)
- **D(z)**: A **controller** TF to do the job (what we want here)
- **H(z)**: The final desired TF between **R** (reference) and **Y** (output)
- Thus[2]:

$$\boxed{\begin{aligned} H(z) &= \frac{DG}{1+DG} \\ \rightarrow D(z) &= \frac{1}{G}\frac{H}{1-H} \end{aligned}}$$

- This calls for a **D(z)** that will **cancel the plant effects** and that will **add whatever is necessary to give the desired result**. The problem is to discover and implement constraints on **H(z)** so that we do not ask for the impossible.
  - This implies that we **need some constraints** on both **H(z)** and **D(z)**

1: Transfer Function

2: Mental Quiz: What does **1+DG** say about the sign of the feedback (positive or negative)? That is, what is the characteristic equation for a system with positive feedback?

Direct Design Method Of Ragazzini [2]: Design Constraints: I. Causality

- Remember/Recall an Interesting Point:
  - From z-transform theory we know that **if** **D(z)** is causal, **then** as $z \rightarrow \infty$ its transfer function is well behaved & it **does not** have a pole at infinity.

- $D(z) = \frac{1}{G}\frac{H}{1-H}$ implies that **if** **G(z)** = 0 (at ∞), **then** **D(z)** would have a pole (at ∞) **unless H(z)** cancels it.

∴

H(z) must have a zero (at ∞) of the same order as G**(z)**'s 0s (at ∞)

→ Which means: **If** there is a lag in the plant (**G(z) starts with** z^{-l}) **then** causality requires that the delay of **H(z)** is that the closed-loop system must be at least as long a delay of the plant.

(Whoa! It might sound deep, but it's rather intuitive ☺)

Direct Design Method Of Ragazzini [3]: Design Constraints: II. Stability

- The characteristic equation and the closed loop roots:

$$1 + D(z)G(z) = 0$$

- Define[3] $D = \frac{c}{d}$ and G= $\frac{b}{a}$ ➔ $ad + bc = 0$
- Define $z - \alpha$ as a pole of **G(z)** and a <u>common factor</u> in DG that represents **D(z)** cancelling a pole/zero of **G(z)**.
- **Then** this common factor *remains a factor of the characteristic polynomial.*
- **If** this factor is outside the unit circle, **then** the system is unstable!

∴

1-H(z) must contain as zeros
all the poles of **G(z)** that are outside the unit circle &
H(z) must contain as zeros
all the zeros of G(z) that are outside the unit circle

3: Note the switching of the "alphabetical-ness" of these two fractions

Direct Design Method Of Ragazzini [4]: Design Constraints: III. Steady State Accuracy

- The error from **H(z)** is given by:

$$\mathrm{E(z)} = \mathrm{R(z)}\big(1 - \mathrm{H(z)}\big)$$

- **If** the system is "Type 1" (with a constant velocity/first derivative (K_v)
  - **Then**[4] $E_{ss}^{Step} = 0$ and $E_{ss}^{Ramp} = {}^{1}/_{K_v}$

∴

$$\mathrm{H(z)} = 1$$

&

$$-\mathrm{T_s}\frac{dH(z)}{d(z)}\bigg|_{z=1} = \frac{1}{K_v}\mathrm{H(z)} = 1$$

4: E_{ss}: steady-state error

Direct Design Method Of Ragazzini [5]: An Example

- Consider the plant: $s^2 + s + 1 = 0$

With T_s=1 → z-Transform: $z^2 + 0.786z + 0.368$=0

- Let's design this **system** such that
  - $K_v = 1$
  - Poles at the roots of the plant equation & additional poles as needed

→ $\mathrm{H(z)} = \frac{b_0+b_1 z^{-1}+b_2 z^{-2}+b_3 z^{-3}+\cdots}{1-0.786 z^{-1}+0.368\, z^{-2}}$

I. Causality: $\mathrm{H(z)}|_{z=\infty} = 0 \rightarrow b_0 = 0$

II. Stability: All poles/zeros of G(z) are in the unit circle
   - except for b_0, which is taken care of by $b_0 = [Const] = 0$

III. Tracking:
   - $\mathrm{H(1)} = b_1 + b_2 + b_3 + \cdots = 1 \cdot (1 - 0.786 + 0.368)$ &
   - $-\{1\} \left.\frac{dH(z)}{d(z^{-1})}\right|_{z=1} = \frac{1}{\{1\}}$ → $\frac{b_1+2b_2+3b_3+\cdots \;-[-.05014]}{(1-0.786+0.368)}$ (note the z^{-1})
   - Truncate the number of unknowns to 2 "zeros" … thus solve for b_1 and b_2 (& set $b_3, b_4, \ldots$=0)

∴ $\mathrm{H(z)} = \frac{b_1 z+b_2}{z^2-0.786z+0.368}$ →

$$D(z) = \frac{(z-1)(z-0.9048)(0.6321)}{(0.04837)(z+0.9672)} \frac{(z-0.07932)}{(z-1)(z-0.4180)}$$

$$= 13.07 \frac{(z-0.9048)}{(z+0.9672)} \frac{(z-0.07932)}{(z-0.4180)}.$$

Digital Controls (Magic PID Made Easy Equations)

Implementation of Digital PID Controllers

We will consider the PID controller with an s-domain transfer function

$$\frac{U(s)}{X(s)} = G_c(s) = K_P + \frac{K_I}{s} + K_D s. \tag{13.54}$$

We can determine a digital implementation of this controller by using a discrete approximation for the derivative and integration. For the time derivative, we use the **backward difference rule**

$$u(kT) = \left.\frac{dx}{dt}\right|_{t=kT} = \frac{1}{T}(x(kT) - x[(k-1)T]). \tag{13.55}$$

The z-transform of Equation (13.55) is then

$$U(z) = \frac{1 - z^{-1}}{T}X(z) = \frac{z-1}{Tz}X(z).$$

The integration of $x(t)$ can be represented by the **forward-rectangular integration** at $t = kT$ as

$$u(kT) = u[(k-1)T] + Tx(kT), \tag{13.56}$$

Source: Dorf & Bishop, Modern Control Systems, §13.9, pp. 1030-1

Implementation of Digital PID Controllers (2)

where $u(kT)$ is the output of the integrator at $t = kT$. The z-transform of Equation (13.56) is

$$U(z) = z^{-1}U(z) + TX(z),$$

and the transfer function is then

$$\frac{U(z)}{X(z)} = \frac{Tz}{z-1}.$$

Hence, the z-domain transfer function of the **PID controller** is

$$\boxed{G_c(z) = K_P + \frac{K_I Tz}{z-1} + K_D\frac{z-1}{Tz}.} \tag{13.57}$$

The complete difference equation algorithm that provides the PID controller is obtained by adding the three terms to obtain [we use $x(kT) = x(k)$]

$$\begin{aligned} u(k) &= K_P x(k) + K_I[u(k-1) + Tx(k)] + (K_D/T)[x(k) - x(k-1)] \\ &= [K_P + K_I T + (K_D/T)]x(k) - K_D T x(k-1) + K_I u(k-1). \end{aligned} \tag{13.58}$$

Equation (13.58) can be implemented using a digital computer or microprocessor. Of course, we can obtain a PI or PD controller by setting an appropriate gain equal to zero.

Source: Dorf & Bishop, Modern Control Systems, §13.9, pp. 1030-1

Now, What's Next?

What's Next?

Research:

- Thesis Projects:
  - Signal Processing (Eulerian Video Magnification)
  - Digital Control (OpenROVs)
  - Robotics
  - More!

Courses

- ELEC4620:
  Digital Signal Processing
- ELEC4630:
  Image Processing & Computer Vision
- **METR 4202:**
  Advanced Control & Robotics
- CSSE4010:
  Digital System Design

Economic Signals!

UA Funding Note

- Old

Funding cluster	Part of funding cluster	Maximum student contribution amounts ($)	Australian Government contribution ($)	Total resourcing ($)
Funding cluster 1 Law, accounting, commerce, economics, administration		10,085	1,951	12,036
Funding cluster 2 Humanities		6,044	5,419	11,463
Funding cluster 3 Mathematics, statistics, behavioural science, social studies, computing, built environment, other health	Mathematics, statistics, computing, built environment or other health	8,613	9,587	18,200
	Behavioural science or social studies	6,044		15,631
Funding cluster 4 Education		6,044*	9,974	16,018
Funding cluster 5 Clinical psychology, allied health, foreign languages, visual and performing arts	Clinical psychology, foreign languages, or visual and performing arts	6,044	11,790	17,834
	Allied health	8,613		20,403
Funding cluster 6 Nursing		6,044*	13,163	19,207
Funding cluster 7 Engineering, science, surveying	Engineering, science, surveying	8,613	16,762	25,375
Funding cluster 8 Dentistry, medicine, veterinary science, agriculture	Dentistry, medicine or veterinary science	10,085	21,273	31,358
	Agriculture	8,613		29,886

- New

Funding tier	Discipline(s) within funding tier	Australian Government contribution
Funding tier 1	Law, Accounting, Administration, Economics, Commerce	$1,805
Funding tier 2	Humanities, Social Studies, Communications (excluding Audio-Visual)	$6,021
Funding tier 3	Computing, Behavioural Science, Welfare Studies, Education, Visual And Performing Arts, Built Environment, Other Health	$9,033
Funding tier 4	Mathematics, Clinical Psychology, Allied Health, Nursing, Engineering, Science, Surveying, Environmental Studies, Foreign Languages	$12,045
Funding tier 5	Dentistry, Medicine, Veterinary Science, Agriculture	$18,067

Economic Signals

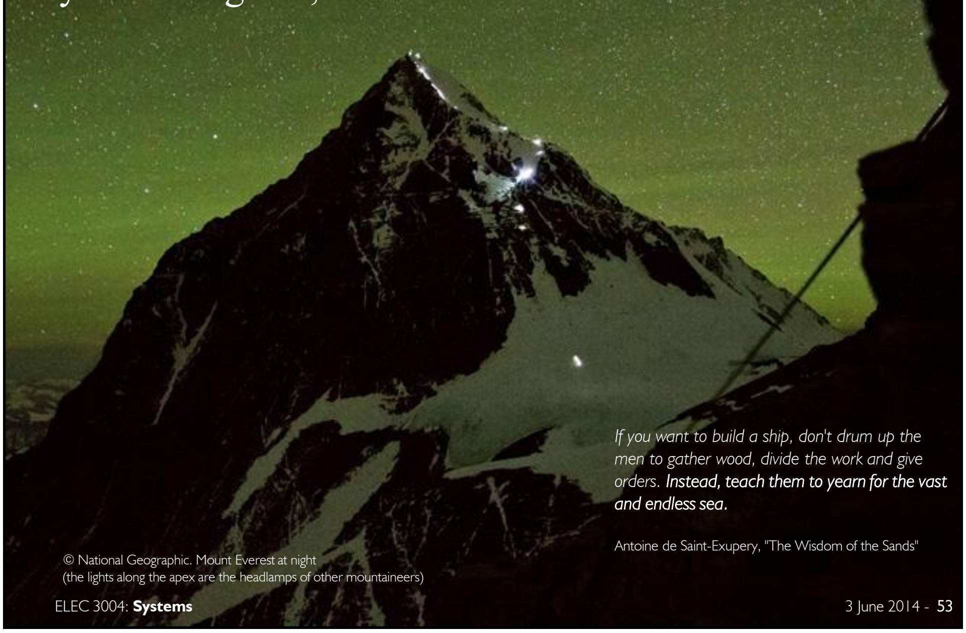
New

- The funding cut is a 28% ($16,762 -> $12,045).
- To keep funding at par would result in a student fee increase of 55% ($8613 to $13330).
- Students would now be paying the majority of the cost (52% compared to the 33% currently).

USA

- Georgia Tech (A$11,450)
- UCSB (A$12,040).
- MIT!
  - $43k/year
  - 90% of students will get financial aid
  - average net price of an MIT education being $38k
  - Median debt at graduation of only $11k.

Now Finally Some Philosophy (I am a Dr of it!!!)
Systems: Signals, Controls…A Fundamental Yearn!



*If you want to build a ship, don't drum up the men to gather wood, divide the work and give orders. **Instead, teach them to yearn for the vast and endless sea.***

Antoine de Saint-Exupery, "The Wisdom of the Sands"

© National Geographic. Mount Everest at night
(the lights along the apex are the headlamps of other mountaineers)