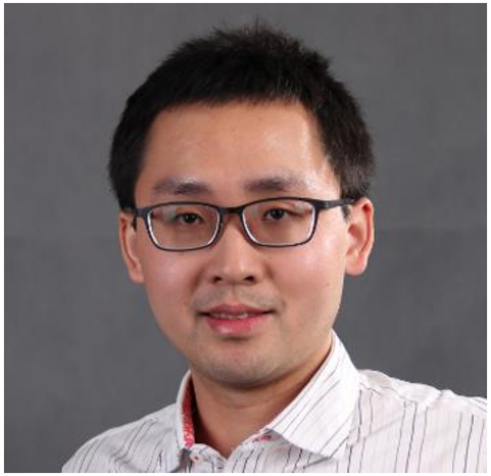
Signals and Systems

Department of Electrical & Electronic Engineering
Southern University of Science and Technology

Spring 2019



WANG Rui

- USTC - CSE - BEng
- HKUST - ECE - PhD
- Huawei - Senior Research Engineer
- SUSTech – EEE - Associate Professor

Research Interests:

- Wireless communications: 5G, VLC, mmWave and etc.
- Cloud and edge computing
- Stochastic optimization, Reinforcement learning, convex optimization and etc.

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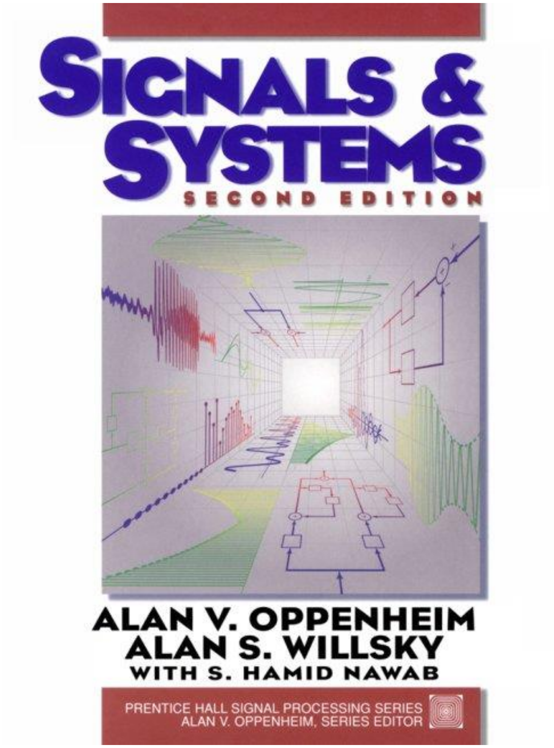
- “Signals and Systems”, Oppenheim, Willsky and Nawab, 2nd Edition, 1997, Prentice-Hall.

- This course teaches Chapters 1 to 10.
  - Roughly two weeks for one chapter
  - Middle-term exam for Chapters 1 to 4
  - Chapters 6, 8, 9, 10 in a short manner
  - Final exam for all



Textbook reading is crucial, as I cannot cover every detail in slides

Three Pillars

Lectures (Tutorial)

Matlab Labs

YOU

Assignment/Quiz

Mid-term Exam

Final Exam

Lab Reports

Project Report & Presentation

Class Schedules

- **Lab Session – Starts at the second week**
- **Instructor: Dr. Guang Wu(吴光)**

- **Tutorials – Time/location TBD for this year**
- **Every week (no for week 1)**

- **TA：TBD.**

Practice is Important

- **Which taste of 粽子 do you like? Salty or sweet**
- **How can a southern Chinese get used to sweet 粽子?**

- **Assignment: Every week (no for week 1)**
- **Submit assignment in hardcopy after one week to tutor at Lab course.**
- **Late submission will have 20% reduction each day for the assignment score.**

信号与系统2019

扫一扫二维码，加入该群。

Signals and Systems

- Signals: everything which carries information
- Systems: everything which processes input signal and generate output signal

Slides partly extracted from "Signals and Systems", Lecture Notes by Prof. Qing Hu, MIT, 2004, and Prof. Linshan Lee, NTU, 2009

Communication Signals & Systems

Can you find any example of signals and systems when making a phone call?

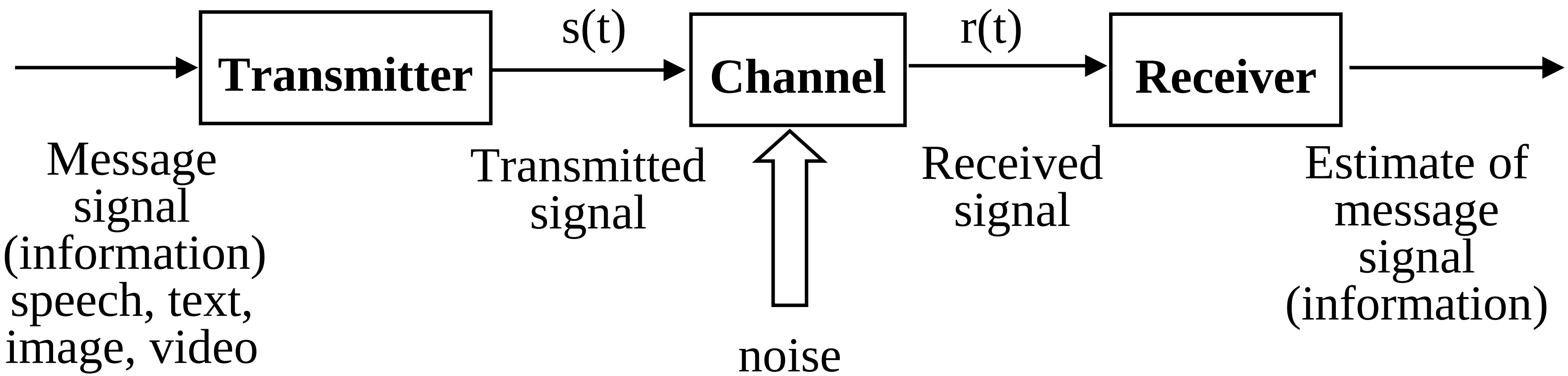
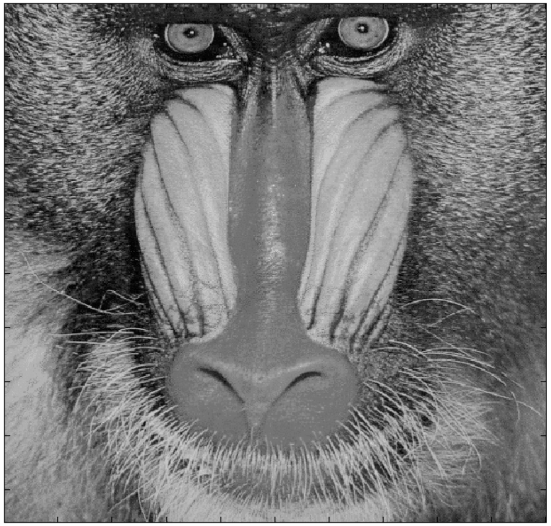
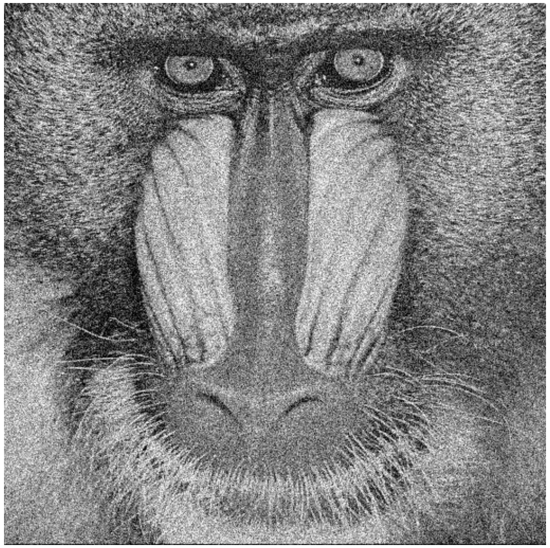


Image Processing





More examples of signals

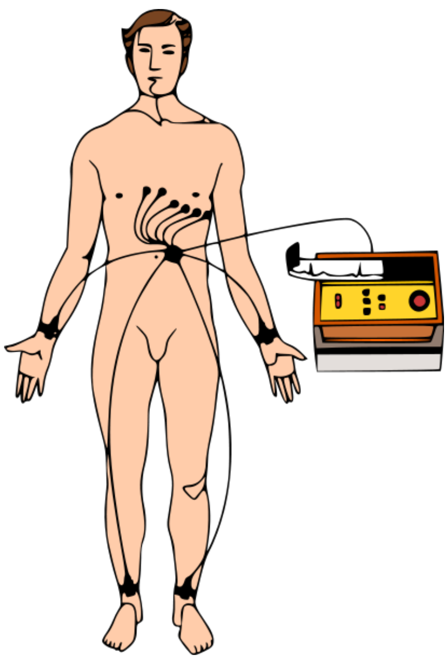
- Electrical signals – voltages and currents in a circuit
- Acoustic signals – audio or speech signals
- Video signals – movie
- Biological signals – sequence of bases in a gene
- We will treat noise as unwanted signals.

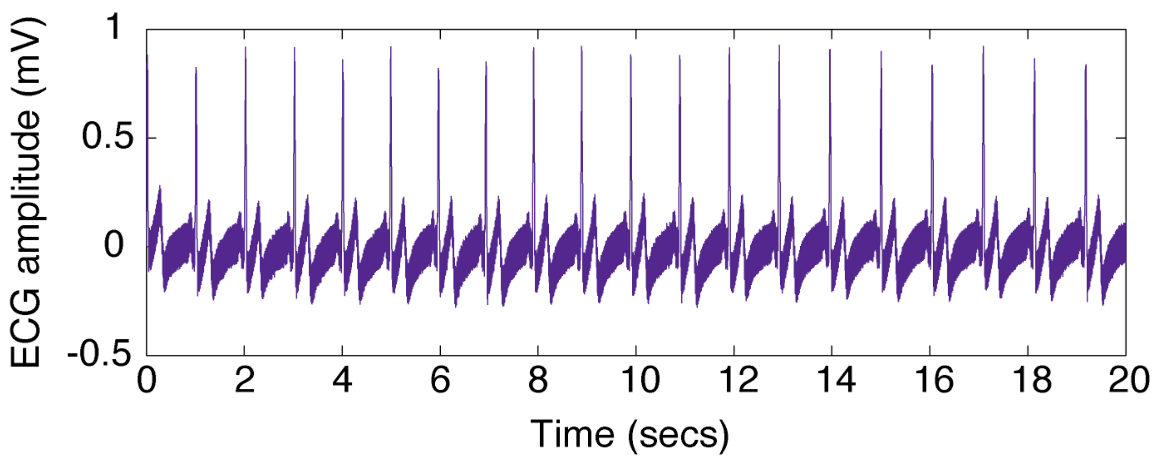
Signals and Systems from Our Point of View

- Signals are variables that carry information, like function.
- Systems process input signals to produce output signals.
- The course is about using mathematical techniques to analyze and synthesize systems which process signals.

Independent Variable

- Time is often the independent variable. Example: the electrical activity of the heart recorded with chest electrodes — the electrocardiogram (ECG).





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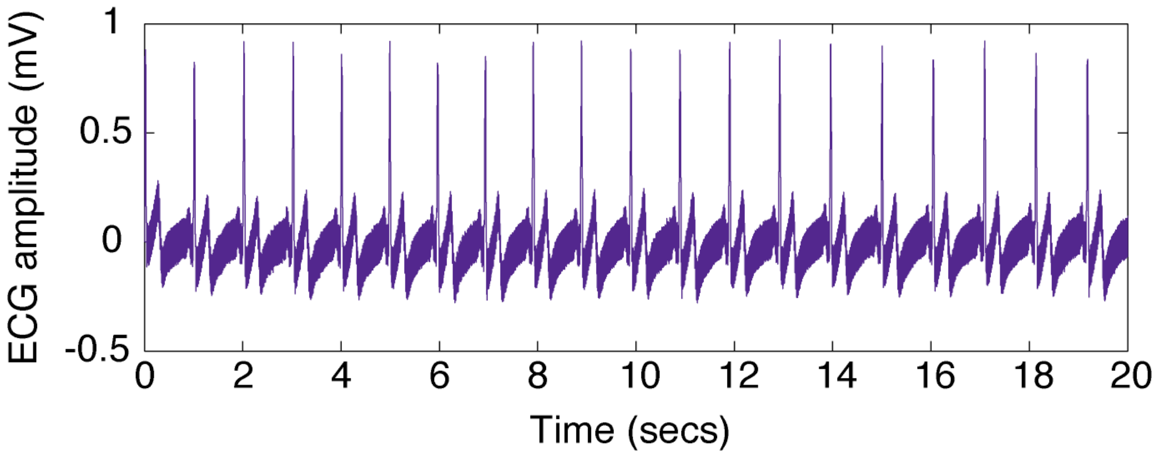
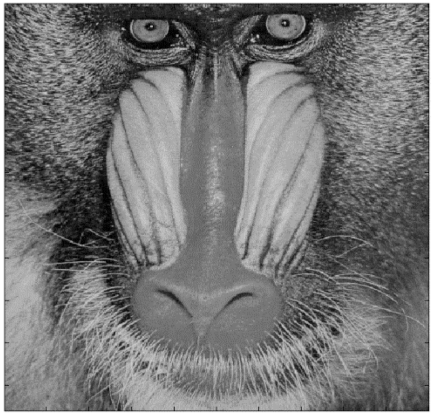
Signal Classification 1: Independent Variable Dimensionality

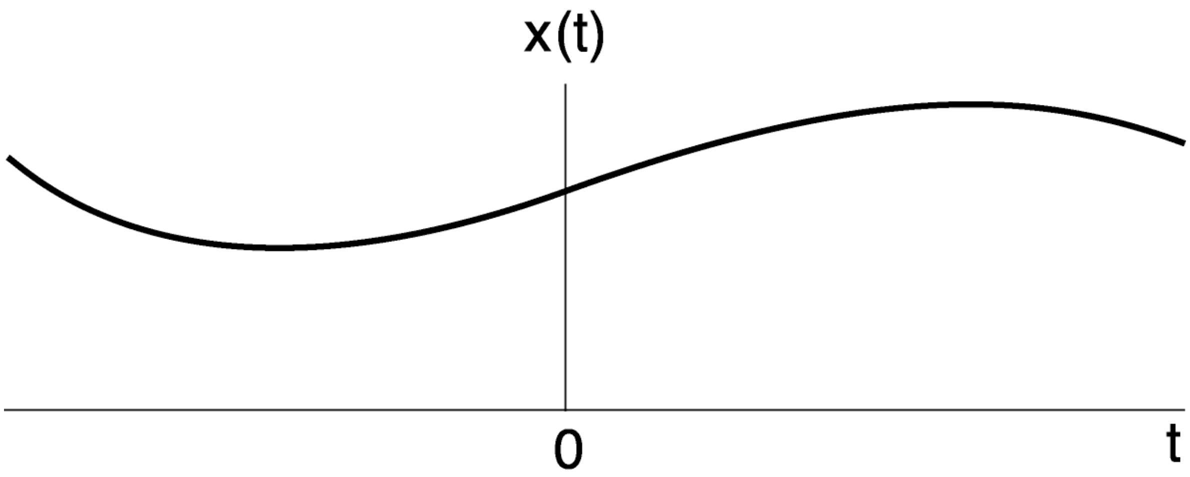
- An independent variable can be 1-D (*t* in the ECG), 2-D (*x*, *y* in an image), or 3-D (*x*, *y*, *t* in an video).





- We focus on 1-D for mathematical simplicity but the results can be extended to 2-D or even higher dimensions.

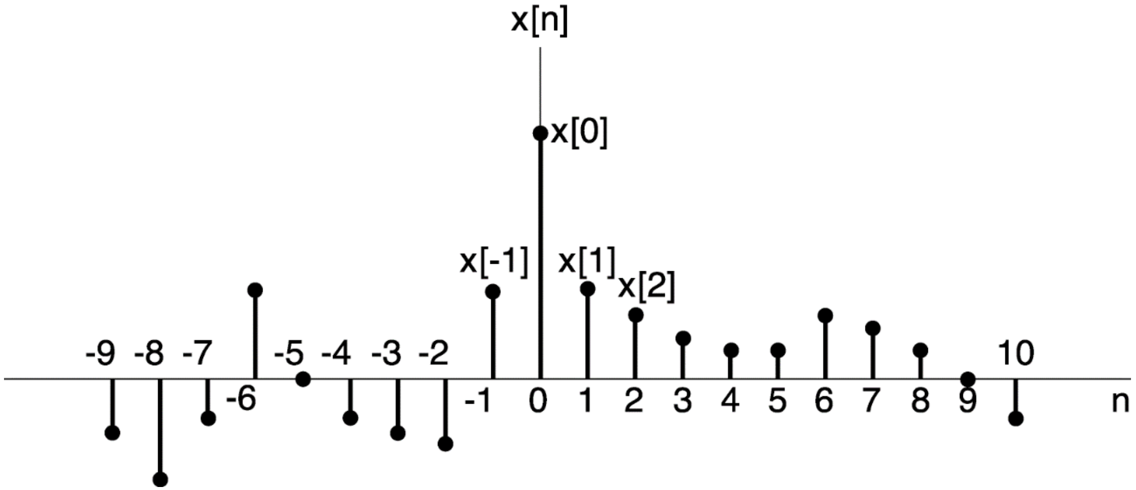
Signal Classification 2: Continuous-time (CT) Signals



- Independent variable is continuous
- Most of the signals in the physical world are CT signals.
- E.g. voltage & current, pressure, temperature, velocity, etc.

Notation: x(t)

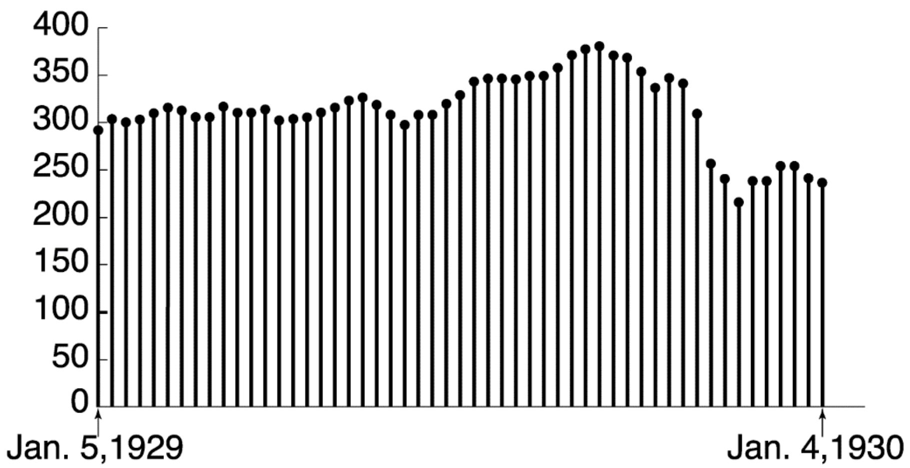
Discrete-time (DT) Signals



- Independent variable is integer
- Examples of DT signals: DNA base sequence, population of the *n*-th generation of certain species

Notation: $x[n]$

Many Human-made Signals are DT

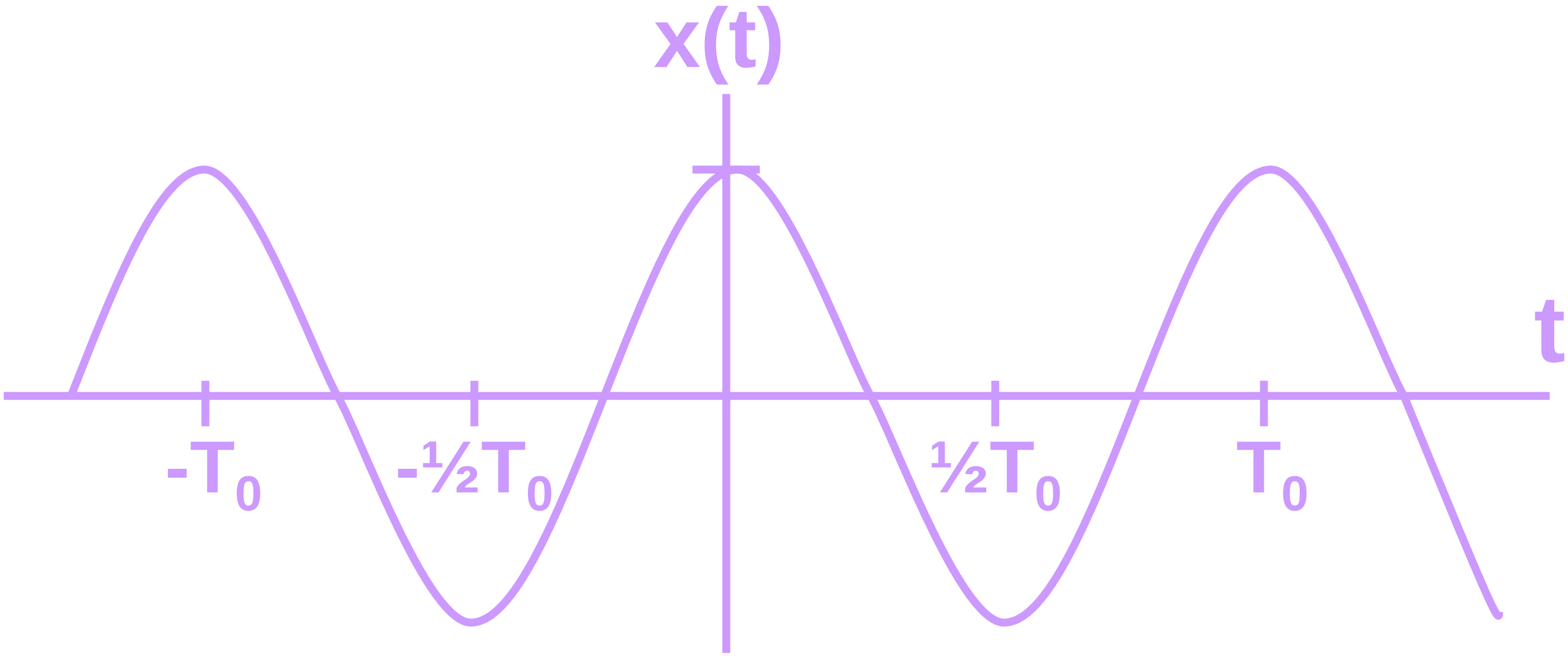


Weekly Dow-Jones industrial average

Digital image

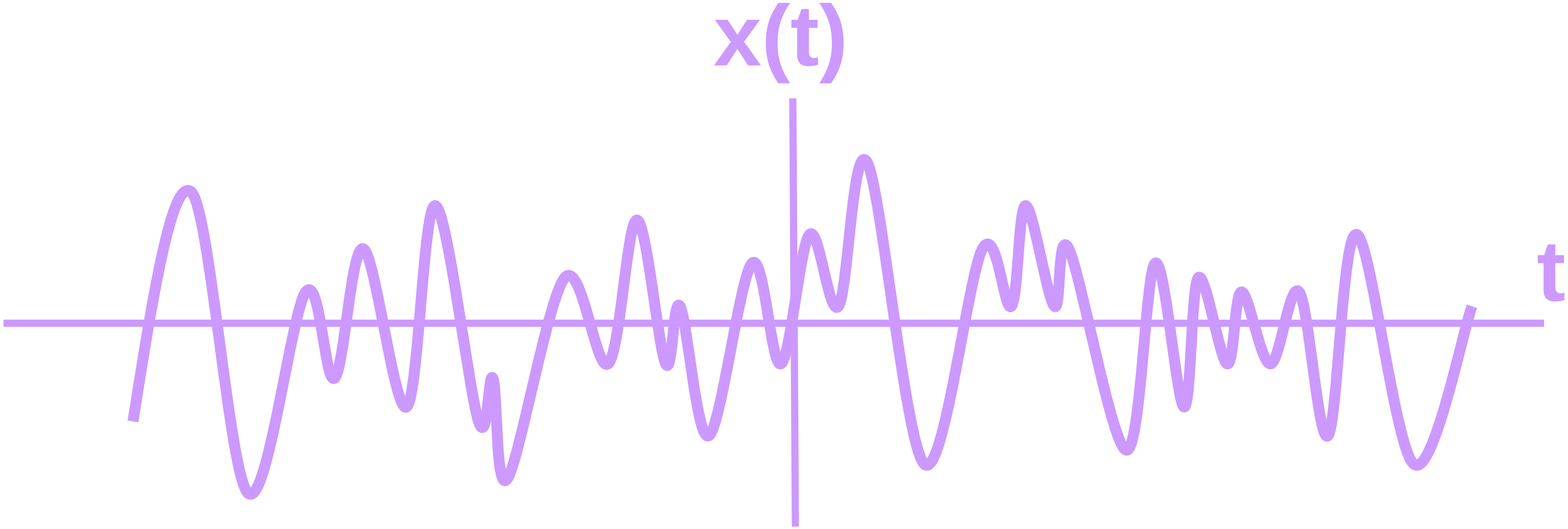
- Why DT? — Can be processed by modern digital computers and digital signal processors (DSPs).

Signal Classification 3: Deterministic Signal



- Each value of the signal is fixed, and can be determined by a mathematical expression, rule, or table.
- Future values of the signal can be calculated from past values with complete confidence.

Signal Classification 3: Random Signal



- Having a lot of uncertainty about its behaviour.
- Future values cannot be accurately predicted, and can usually only be guessed based on the averages of sets of signals.

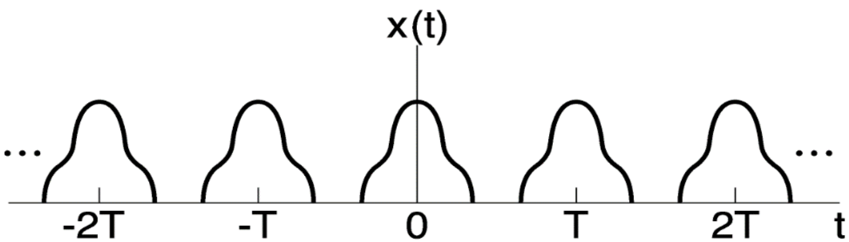
Classification 4: Periodic / Aperiodic

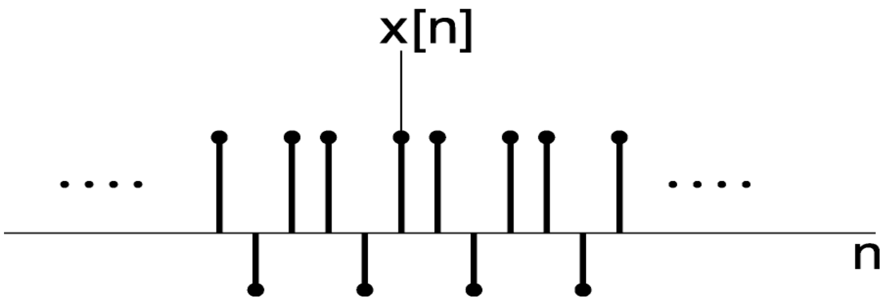
- Periodic Signals

  CT: $x(t) = x(t + T)$, T : *period*

  $x(t) = x(t + mT)$,   *m: integer*

  DT: $x[n] = x[n + N]=x[n + mN]$, N: period



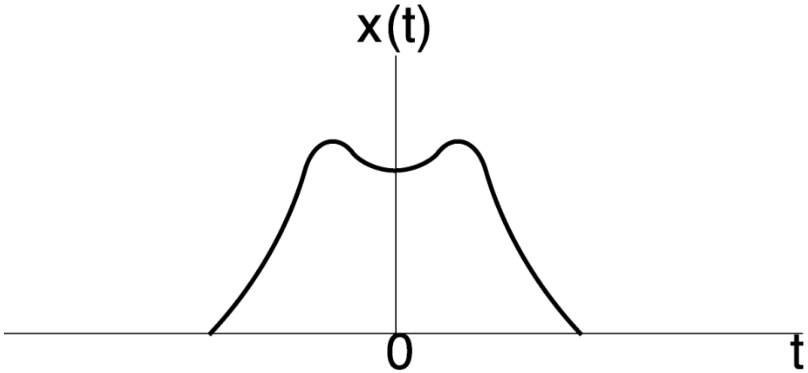


- Fundamental period: the smallest positive period

- Aperiodic: NOT period

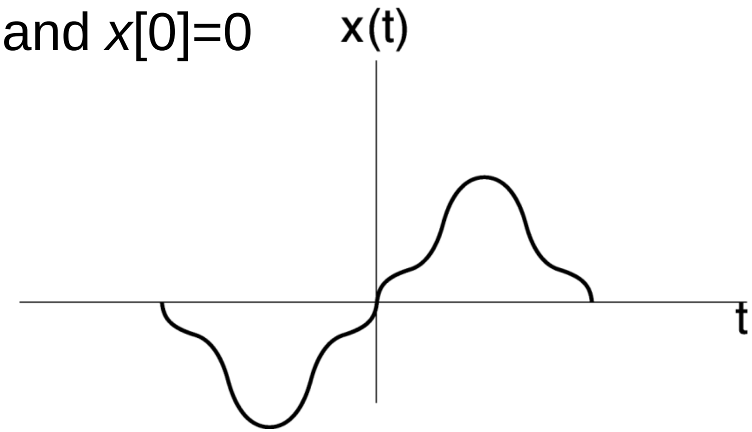
Classification 5: Even / Odd

- Even and Odd Signals
  - Even $x(t) = x(-t)$ *or* $x[n] = x[-n]$



Example: cos(t)

  - Odd $x(t) = -x(-t)$ *or* $x[n] = -x[-n]$
    - $x(0)=0$, and $x[0]=0$



Example: sin(t)

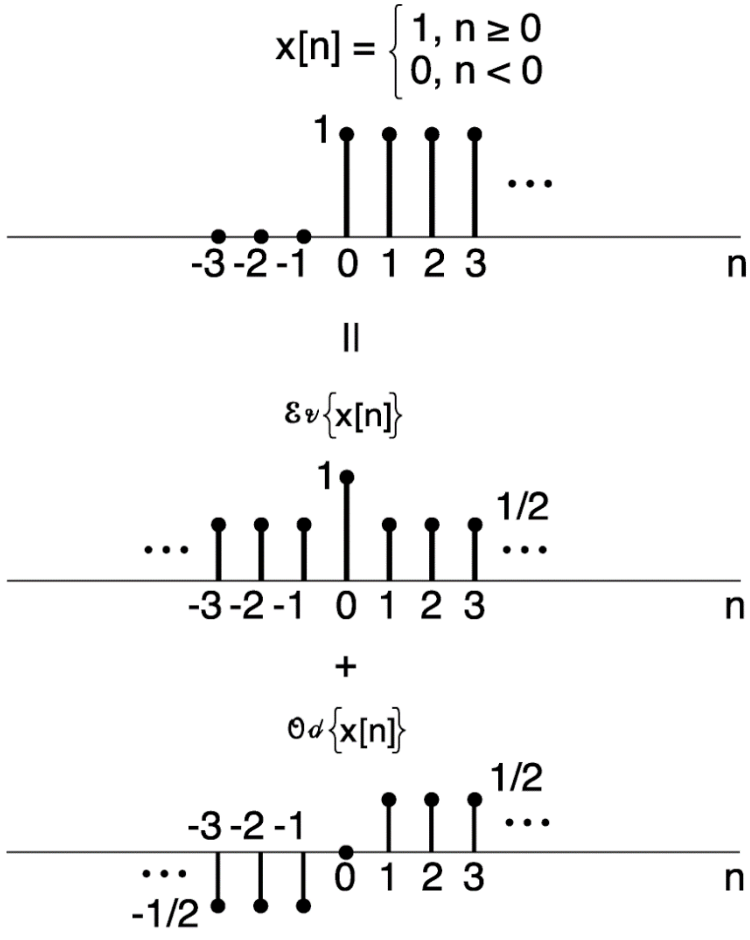
- Any signals can be expressed as a sum of *Even* and *Odd* signals. That is:

$$x(t) = x_{even}(t) + x_{odd}(t),$$

where:

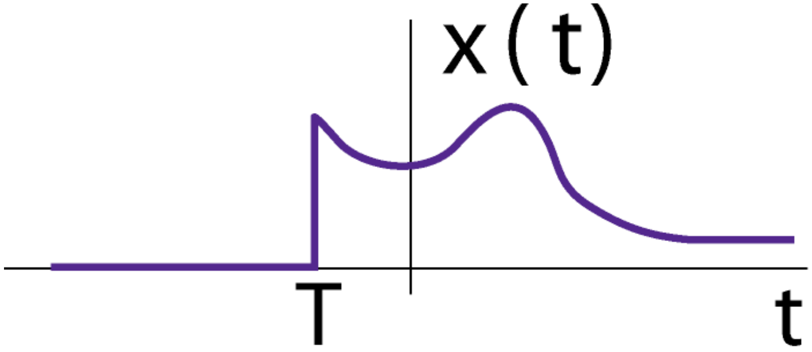
$$x_{even}(t) = [x(t) + x(-t)]/2,$$

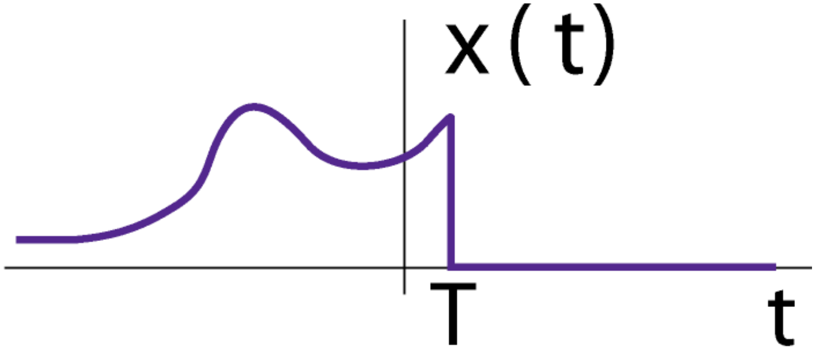
$$x_{odd}(t) = [x(t) - x(-t)]/2.$$



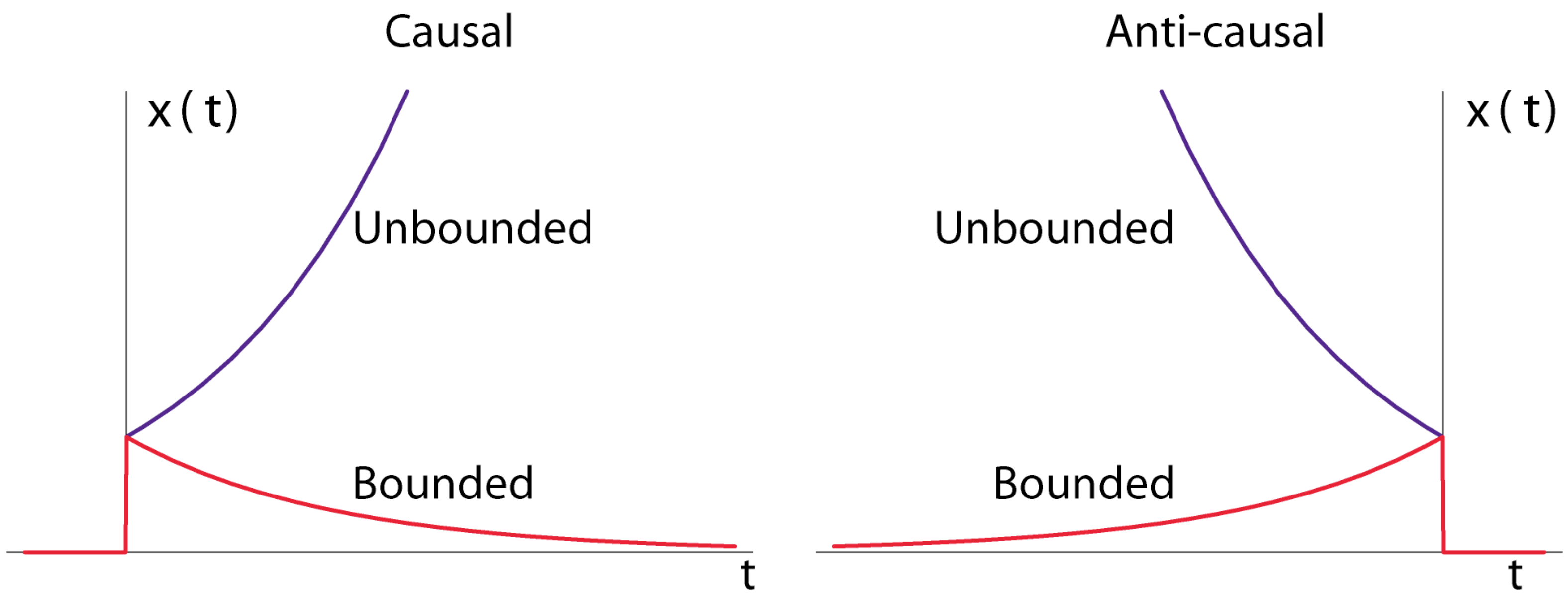
Classification 6: Right- and Left-Sided

- A right-sided signal is zero for $t < T$, and
- A left-sided signal is zero for $t > T$, where T can be positive or negative.



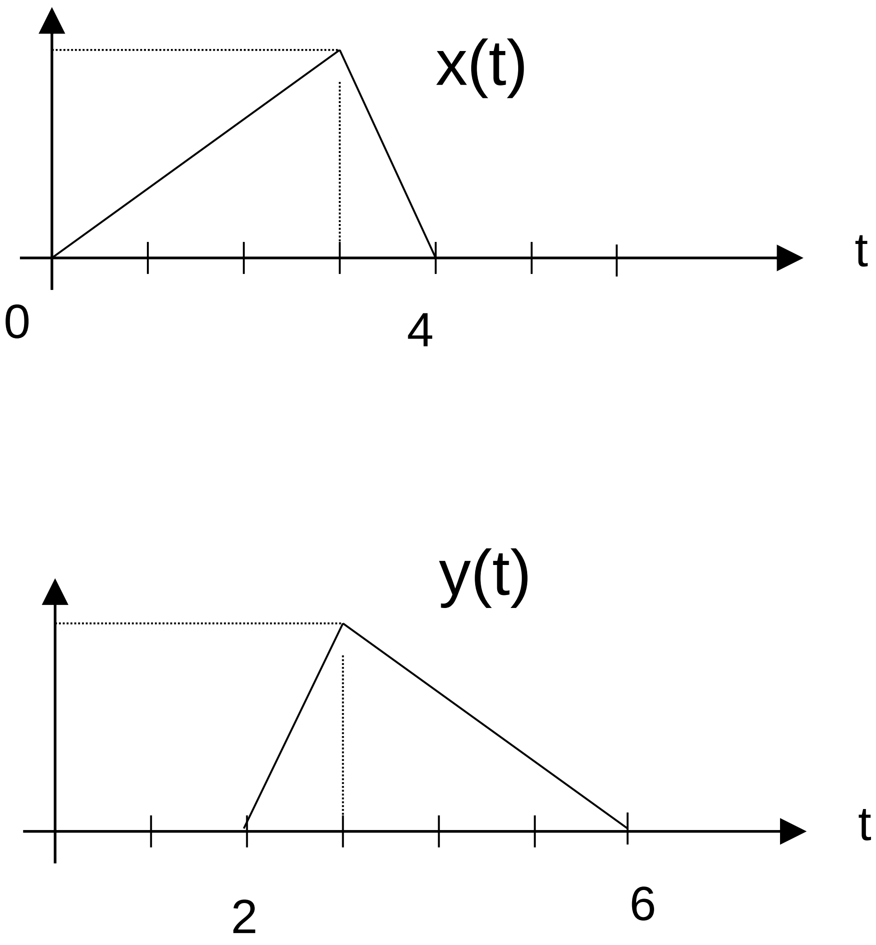


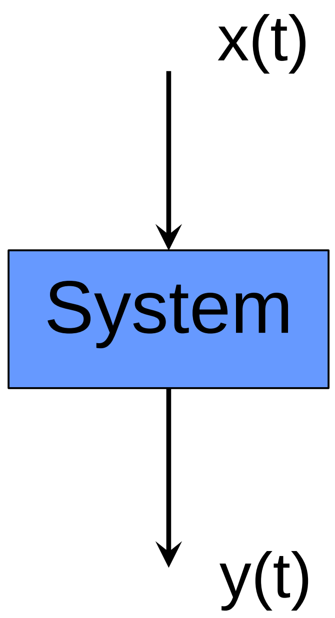
Classification 7: Bounded and Unbounded



- Bounded signal: the absolute value of signal is bounded.
- Unbounded signal: otherwise

Transformation of a Signal





Transformation of a Signal

- Time Shift

$$x(t) \to x(t - t_0) \quad , \quad x[n] \to x[n - n_0]$$

- Time Reversal

$$x(t) \to x(-t) \quad , \quad x[n] \to x[-n]$$

- Time Scaling

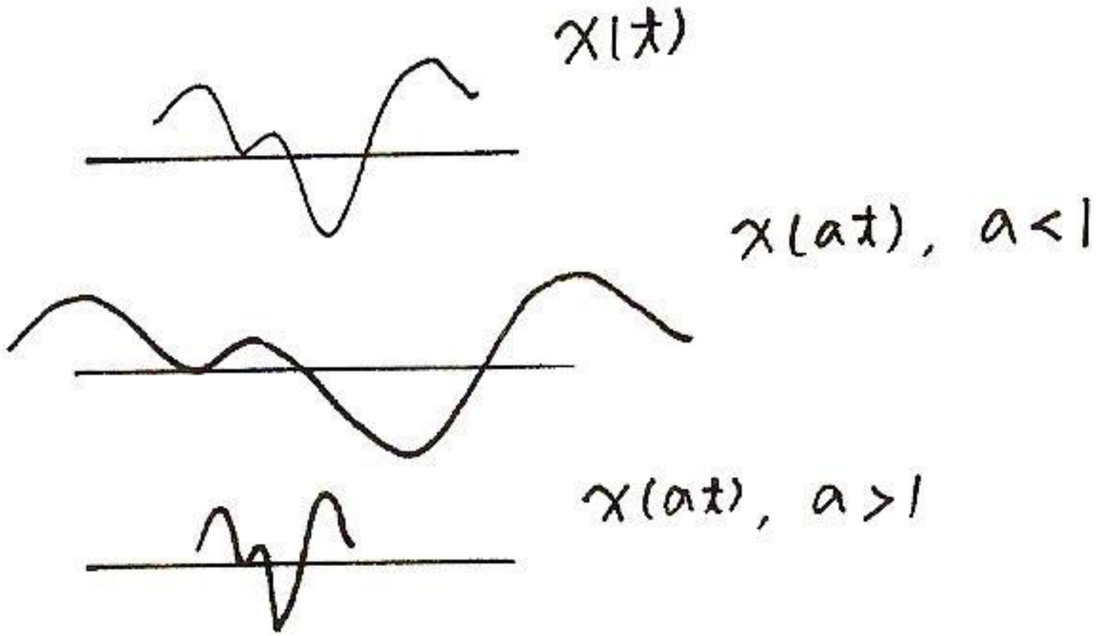
$$x(t) \to x(at) \quad , \quad x[n] \to ?$$

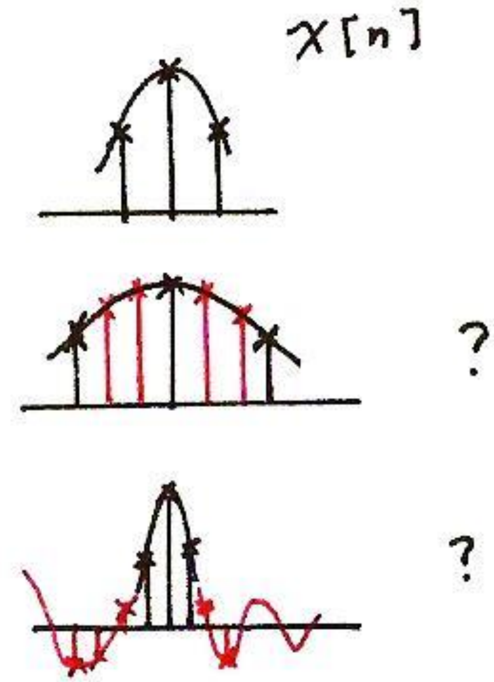
- Combination

$$x(t) \to x(at + b) \quad , \quad x[n] \to ?$$

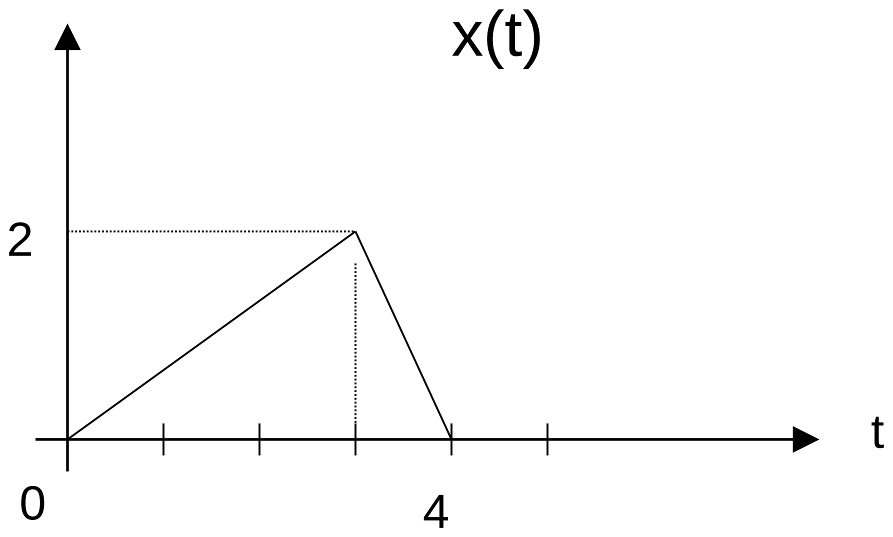
Transformation of a Signal

Time Scaling





Class problem

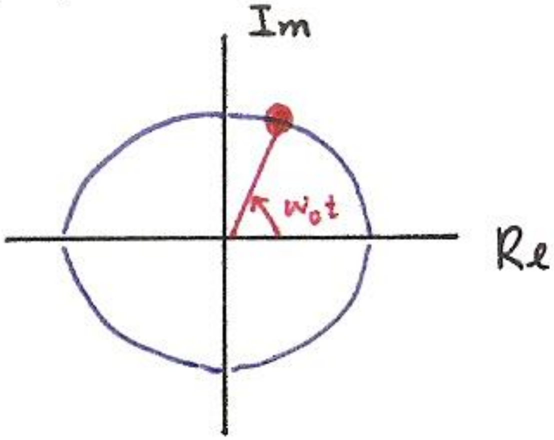


x(-2t+2) ?

Exponential Signals

- A very important class of signals is presented as:
  - CT signals of the form $x(t) = e^{j\omega t}$
  - DT signals of the form $x[n] = e^{j\omega n}$
- For both *exponential* CT and DT signals, x is a complex quantity and has:
  - a real and imaginary part [i.e., *Cartesian form*], or equivalently
  - a magnitude and a phase angle [i.e., *polar form*].
- We will use whichever form that is convenient.

$$x(t) = e^{j\omega_0 t}$$

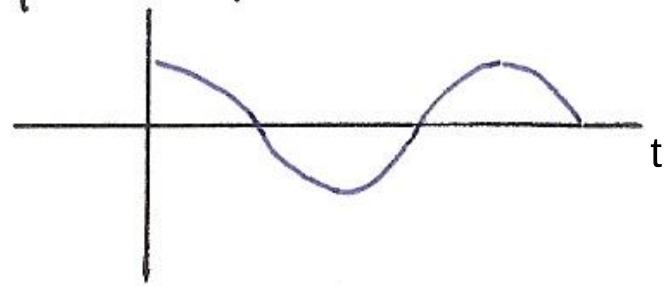


Euler's relation

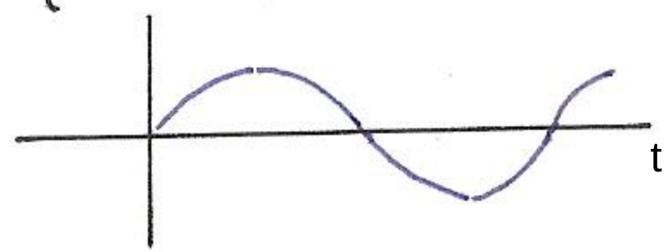
$$e^{jx} = \cos x + j\sin x$$

$\omega_0 t$ is defined as phase

$$\mathrm{Re}\{e^{j\omega_0 t}\} = \cos\omega_0 t$$



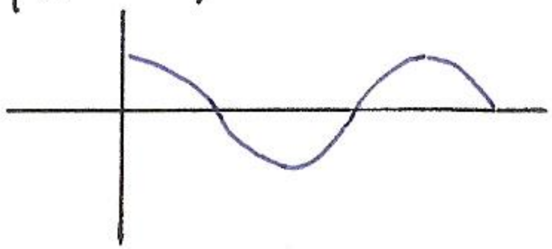
$$\mathrm{Im}\{e^{j\omega_0 t}\} = \sin\omega_0 t$$



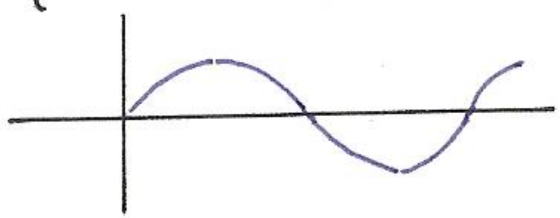
Real and imaginary parts are periodic signals with the same period, but out of phase (90^{o} phase difference)

$$x(t) = e^{j\omega_0 t} = \cos(\omega_0 t) + j\sin(\omega_0 t)$$

$Re\{e^{j\omega_0 t}\} = \cos\omega_0 t$



$Im\{e^{j\omega_0 t}\} = \sin\omega_0 t$



-Fundamental (angular) frequency: ω_0

-Fundamental period: $T_0 = \dfrac{2\pi}{\omega_0}$

-In CT, $e^{j\omega_0 t}$ **always periodic**

-larger ω_0 **=> higher frequency**

$$x[n] = e^{j\omega_0 n} = cos\omega_0 n + \mathrm{j}\ \mathrm{sin}\omega_0 n$$

Is it periodic?

Larger ω_0 => higher frequency?

$$e^{j\pi n} = (e^{j\pi})^n = (-1)^n$$

$$e^{j2\pi n} = (e^{j2\pi})^n = (1)^n = 1$$

Periodicity Properties of DT Complex Exponentials

Important difference between $e^{j\omega_0 n}$ and $e^{j\omega_0 t}$:

- $e^{j\omega_0 n}$ is periodic w.r.t. ω_0

Proof:

$$\boxed{e^{j(\omega_0+m\cdot 2\pi)n} = e^{j\omega_0 n} \cdot e^{jm\cdot 2\pi n} = e^{j\omega_0 n}}$$

- However, $e^{j\omega_0 t}$ *is aperiodic w.r.t.* ω_0

$$\boxed{\forall x \neq 0, e^{j(\omega_0+x)t} = e^{j\omega_0 t} e^{jxt} \neq e^{j\omega_0 t}}$$

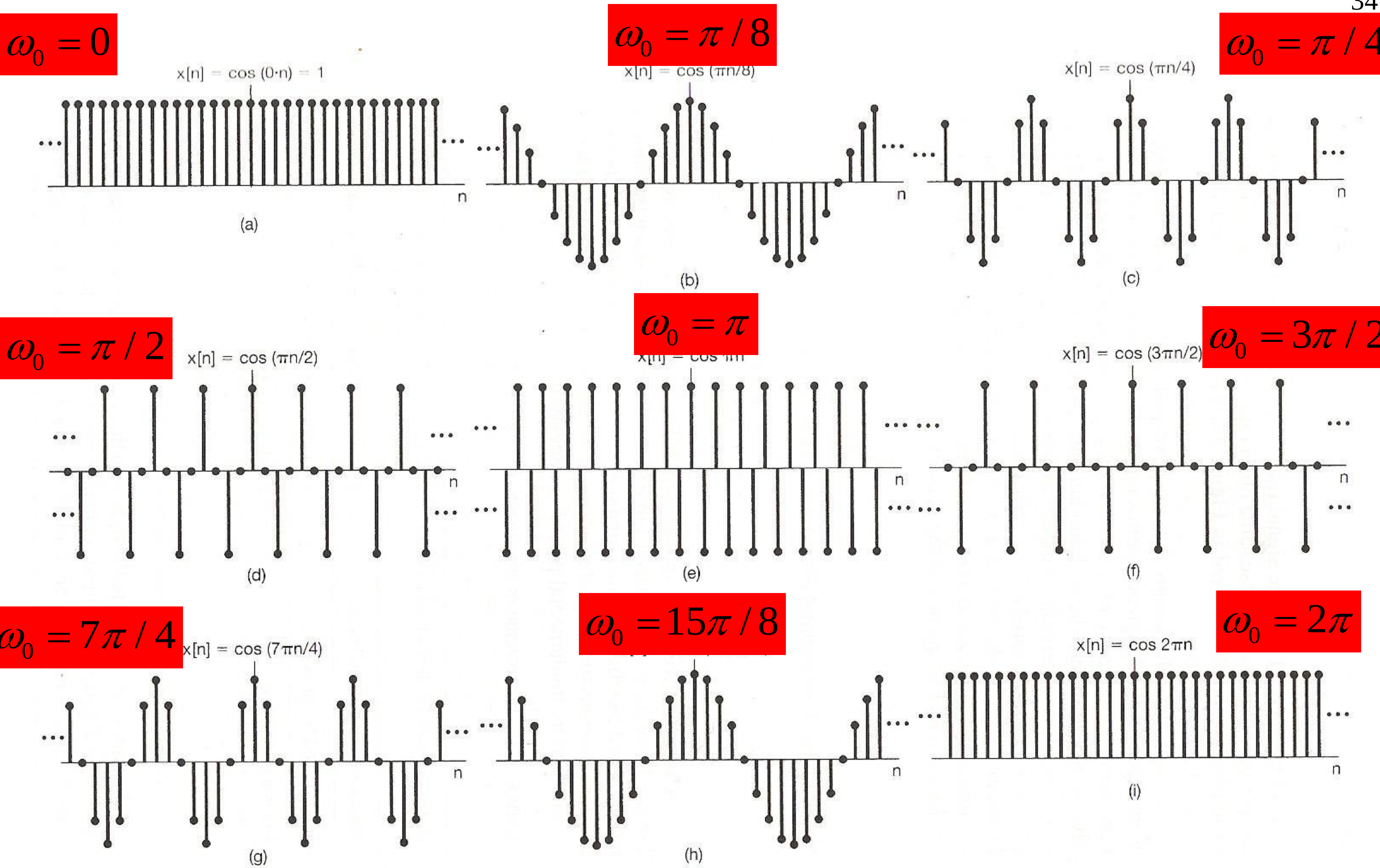


Figure 1.27 Discrete-time sinusoidal sequences for several different frequencies.

Periodicity Properties of DT Complex Exponentials (cont.)

Understanding:

- We need only consider a frequency interval of length 2π, and on most cases, we use the interval: $0 \le \omega_0 < 2\pi$, or $-\pi \le \omega_0 < \pi$

- $e^{j\omega_0 n}$ does ***not*** have a continually increasing rate of oscillation as ω_0 is increased in magnitude.

  lowest-frequency (slowly varying): ω_0 near 0, 2π, …, or 2k • π

  highest-frequency (rapid variation): ω_0 near ± π, …, or (2k+1) • π

$$e^{j(2k+1)\pi n} = e^{j\pi n} = (e^{j\pi})^n = (-1)^n$$

$$e^{j2\pi n} = (e^{j2\pi})^n = (1)^n = 1$$

Harmonically Related Signal Sets

- A set of periodic exponentials which have a common period.

$$\{\phi_k(t) = e^{jk\omega_0 t}, k = 0, \pm 1, \pm 2, \ldots\}$$

Fundamental (Angular) Frequency : $|k\omega_0|$

Fundamental Period: $\dfrac{2\pi}{|k\omega_0|}$

Common Period: $\dfrac{2\pi}{|\omega_0|}$

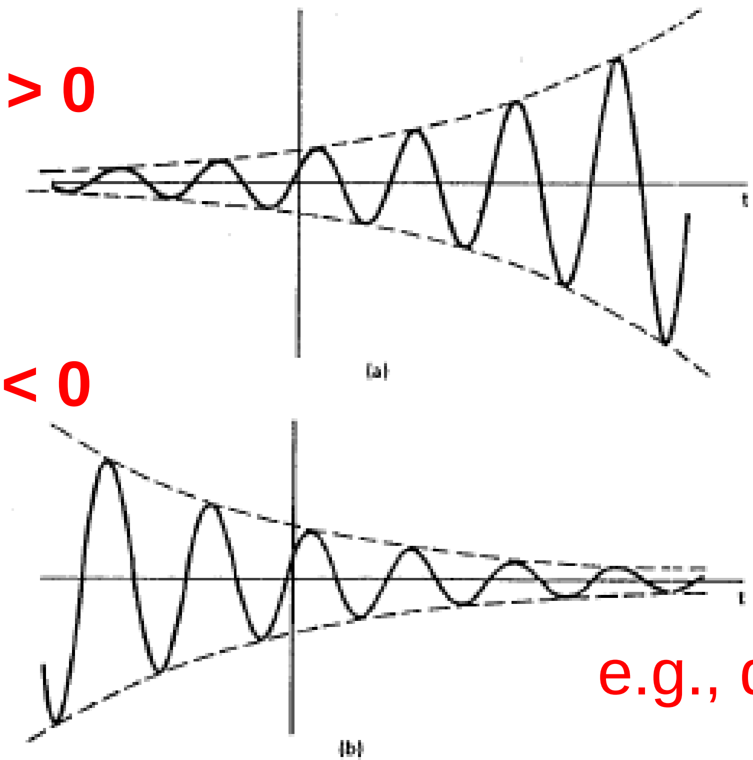
General Complex Exponential Signals - CT

- General format (*C* and *a* are complex numbers)

$$x(t) = Ce^{at} = |C| e^{j\theta} \cdot e^{(r+j\omega_0)t} = |C| e^{rt} \cdot e^{j(\omega_0 t + \theta)}$$

***r* > 0**

***r* < 0**

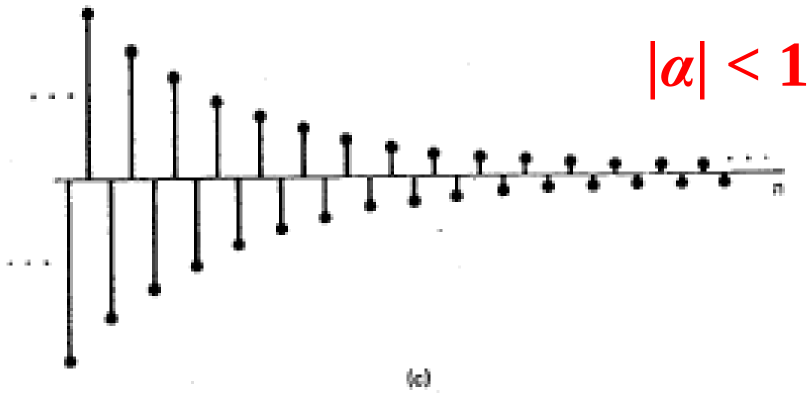


e.g., damped sinusoids

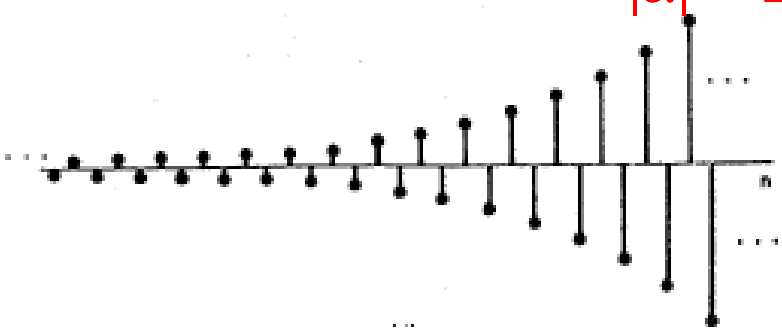
General Complex Exponential Signals - DT

- General format (C and α are complex numbers)

$$x[n] = C\alpha^n = |C|e^{j\vartheta}\cdot|\alpha|^n e^{j\omega_0 n} = |C||\alpha|^n e^{j(\omega_0 n+\vartheta)}$$



$|\alpha| < 1$



$|\alpha| > 1$