Control with Fixed-Rate Limited Feedback

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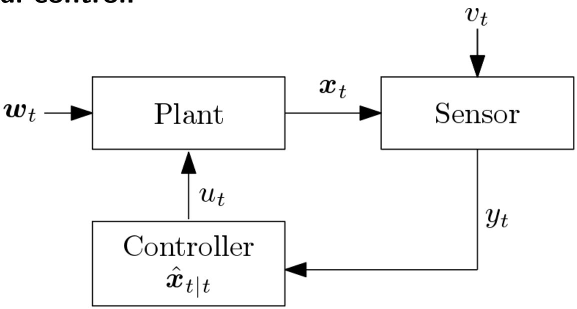
Caltech, Pasadena, CA, USA

ICSEE 2016
Eilat, Israel
November 17, 2016

Networked Control vs. Traditional Control

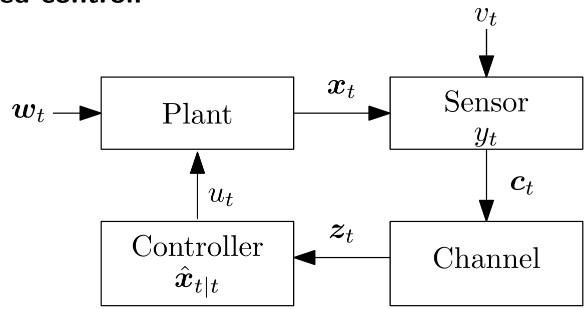
Traditional control:



- Observer and controller are co-located.
- Classical systems are hardwired and well crafted

Networked Control vs. Traditional Control

Networked control:



- Observer and controller are not co-located: connected through noisy link
- Suitable for new remote applications (e.g., remote surgery, self-driving cars)

Linear Quadratic Gaussian Control over Gaussian Channels

Linear quadratic Gaussian (LQG) system

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{B}\mathbf{u}_t + \mathbf{w}_t, \qquad \mathbf{w}_t \sim \text{ i.i.d. } \mathcal{N}(0, \mathbf{W})$$

$$\mathbf{y}_t = \mathbf{C}\mathbf{x}_t + \mathbf{v}_t, \qquad \mathbf{v}_t \sim \text{ i.i.d. } \mathcal{N}(0, \mathbf{V})$$

Noiseless finite-rate channel of rate R

Fixed rate: Exactly R bits are available at every time sample t

Variable rate: R bits are available **on average** at every t

- Transmitter decides on R_t at every t s.t. $\frac{1}{T}\sum_{i=1}^{T} R_t \le R$

LQG cost

$$J = \sum_{t=1}^{T} \left[\mathbf{x}_t^T \mathbf{Q} \mathbf{x}_t + \mathbf{u}_t^T \mathbf{R} \mathbf{u}_t \right] + \mathbf{x}_{T+1}^T \mathbf{F} \mathbf{x}_{T+1}$$

Linear Quadratic Gaussian Control over Gaussian Channels

Scalar Linear quadratic Gaussian (LQG) system

$$x_{t+1} = x_t + u_t + w_t, \qquad w_t \sim \text{ i.i.d. } \mathcal{N}(0, W)$$
$$y_t = x_t + v_t, \qquad v_t \sim \text{ i.i.d. } \mathcal{N}(0, V)$$

Noiseless finite-rate channel of rate R

Fixed rate: Exactly R bits are available at every time sample t

LQG cost

$$J = \sum_{t=1}^{T} \left[Q x_t^2 + R u_t^2 \right] + F x_{T+1}^2$$

Linear Quadratic Gaussian Control over Gaussian Channels

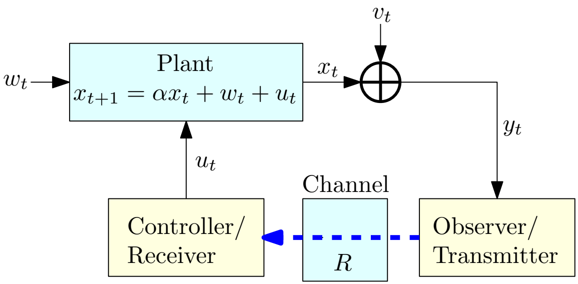
Scalar LQG system

$$x_{t+1} = x_t + u_t + w_t$$

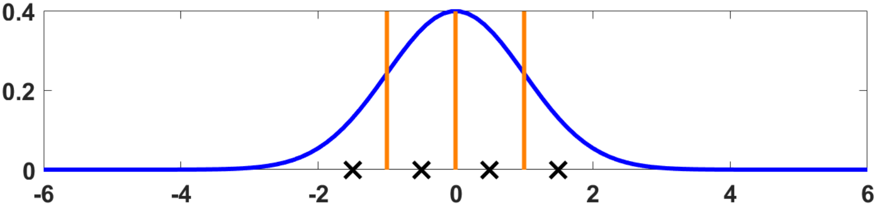
$$y_t = x_t + v_t$$

Finite-rate noiseless channel

Fixed-rate: R bits per time t



Adaptive Fixed-Rate Quantizer



- Use an adjusted quantizer to the input p.d.f.

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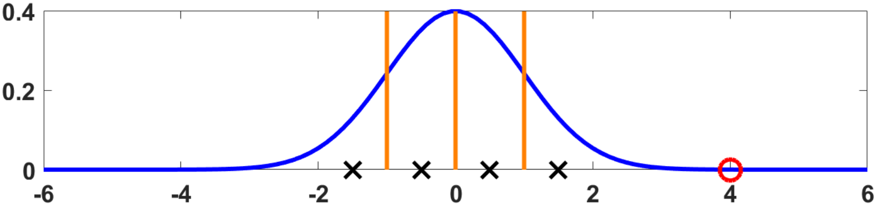

- Use an adjusted quantizer to the input p.d.f.
- At some point a (rare) event will happen
- Input value outside effective quantization interval

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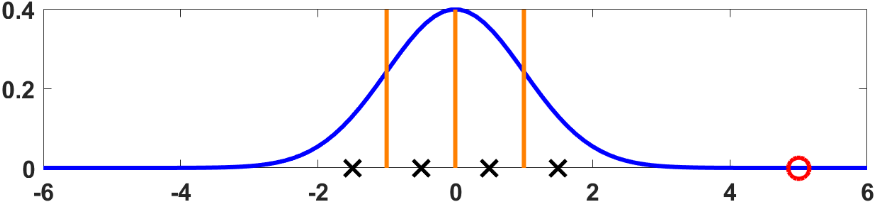

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- Next time instant: Input will be even larger!
- **Avalanche effect**

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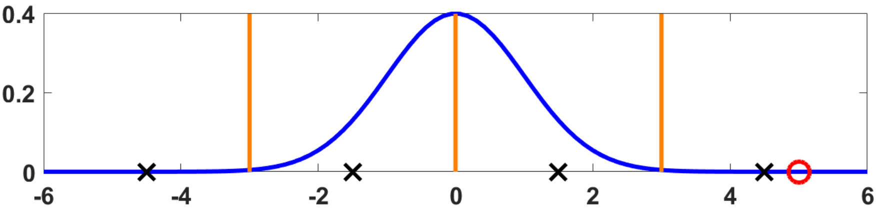


- Use an adjusted quantizer to the input p.d.f.
- At some point a (rare) event will happen
- Input value outside effective quantization interval
- Next time instant: Input will be even larger!
- **Avalanche effect**
- To avoid this ⇒ Quantizer needs to be **adaptive**

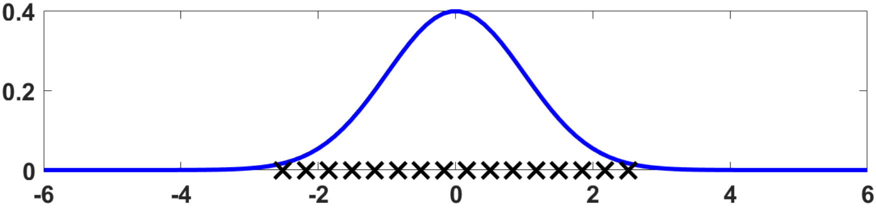
Adaptive Optimal Fixed-Rate Quantizer?

- Adaptive uniform quantizer [Yüksel AC'10]
  - Based on Jayant's adaptive quantizer [Jayant '73]
  - Similar idea in [Brockett-Liberzon AC'00]: "Zooming in/out"
- Adaptive exponential quantizer [Nair-Evans '04]
- Both results prove condition on stabilizability: $R > \log \alpha$
- But no cost optimality claims...
- Other notable contributions: [Borkar-Mitter '97] [Tatikonda-Sahai-Mitter AC'04] [Matveev-Savkin '04] [Tsumura-Maciejowski CDC'03], ...

How to optimize cost?

Optimal Quantizer for One Sample

- Let $x \sim \mathcal{N}(0,1)$
- R bits $\Rightarrow 2^R$ quantization points
- Uniform quantizer is suboptimal
- How to construct an optimal quantizer?



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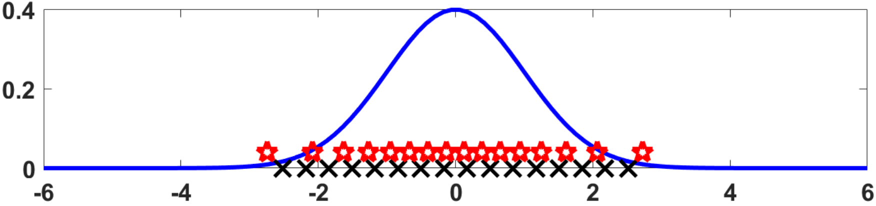


- In general a hard (NP-hard) problem
- Necessary conditions by Lloyd ['57, IT'82] and Max [IT '60]
  - Also known in machine learning as "k-means" clustering

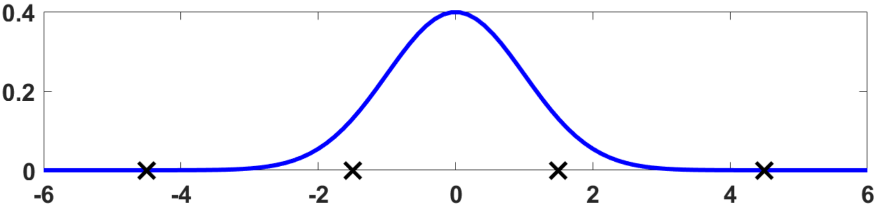
Lloyd-Max Algorithm

Nearest Neighbor: Given reconstruction points, find optimal cells

$$\text{Cell } i = \left\{ x \middle| (x - \hat{x}_i)^2 < (x - \hat{x}_j)^2, \; \forall j \neq i \right\}$$

Centroid: Given quant. cells, find optimal reconstruction points

$$\hat{x}_i = \mathbb{E}\left[x \middle| x \in \text{Cell } i \right]$$



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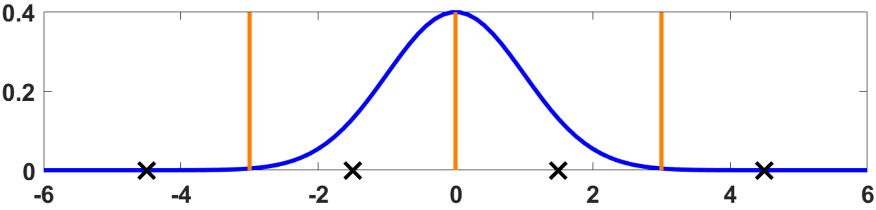

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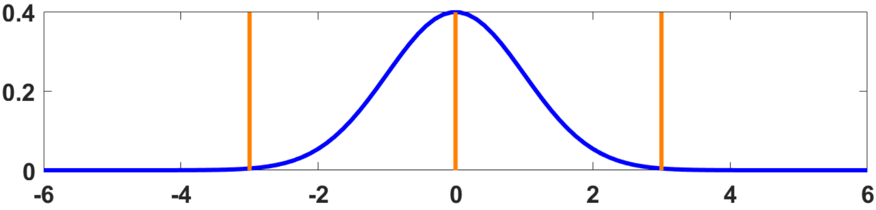

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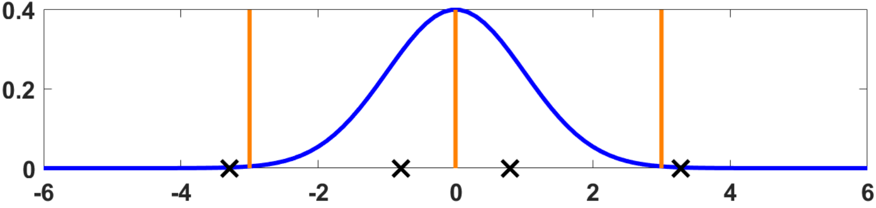

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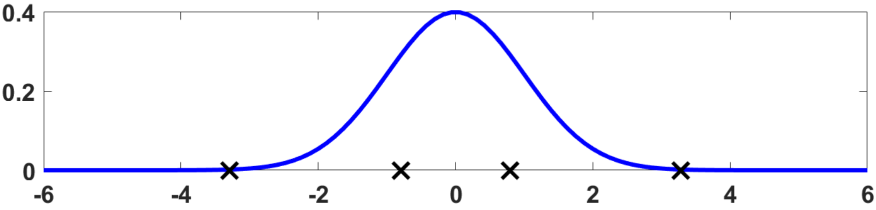

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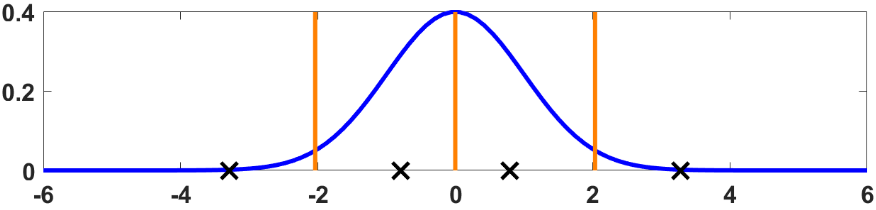

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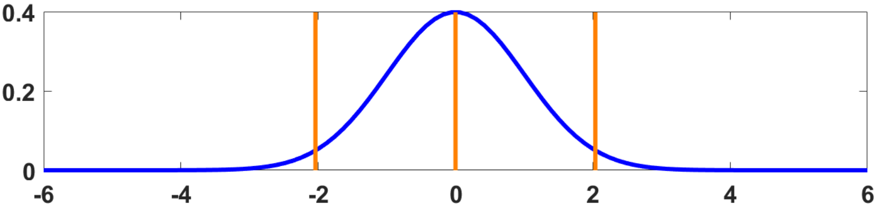

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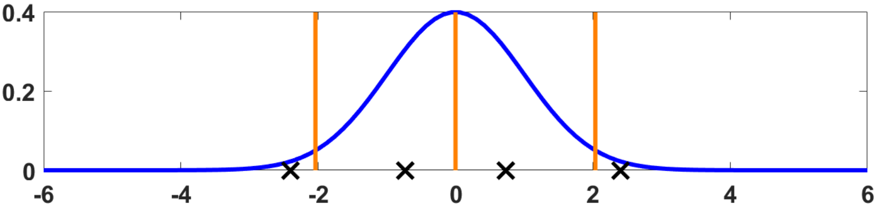

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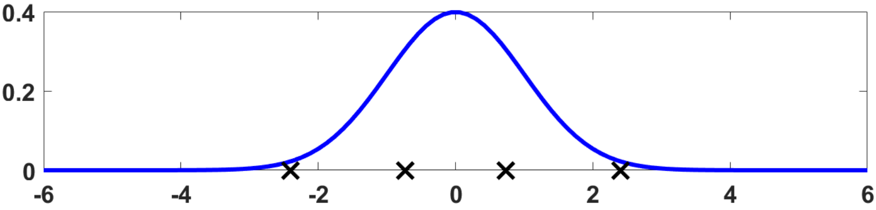

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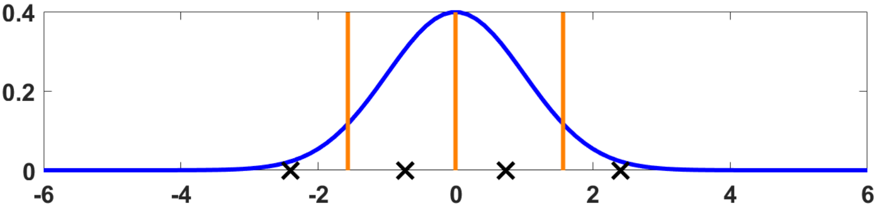

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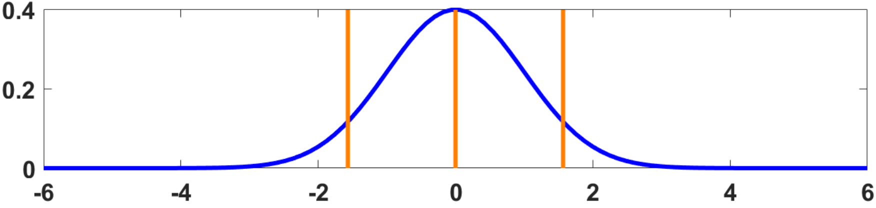

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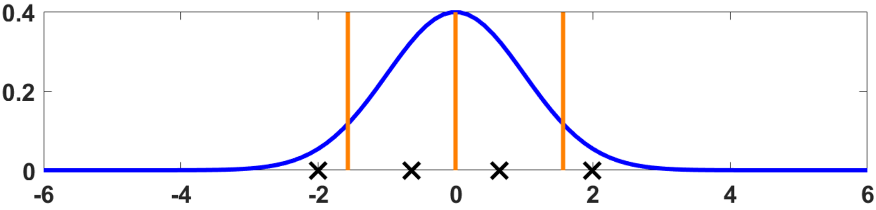

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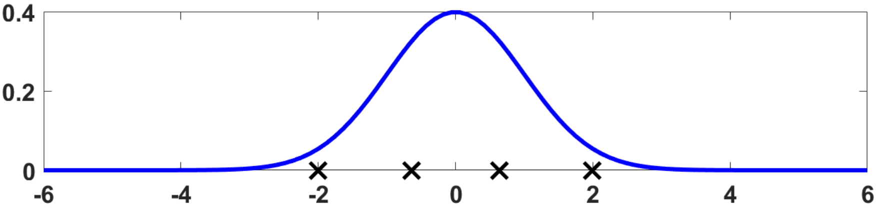

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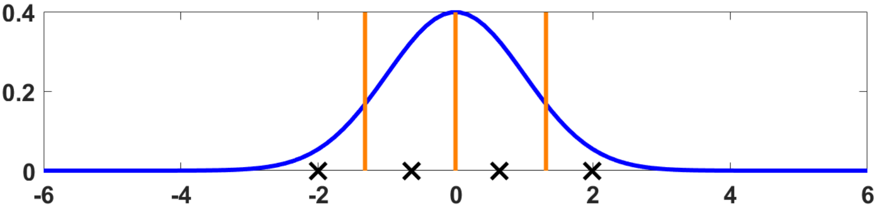

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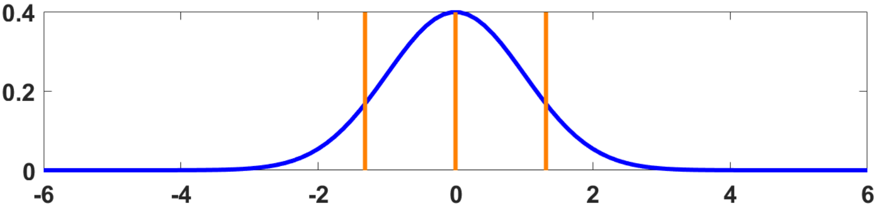

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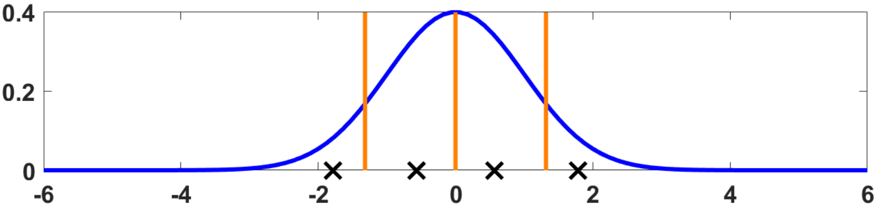

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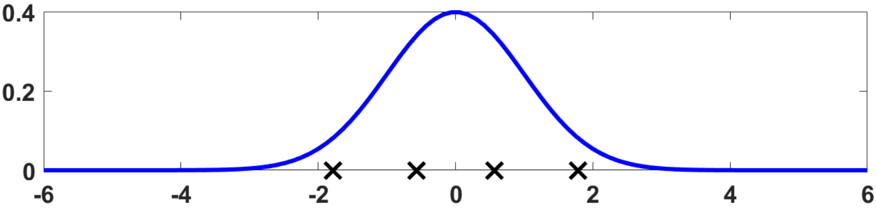

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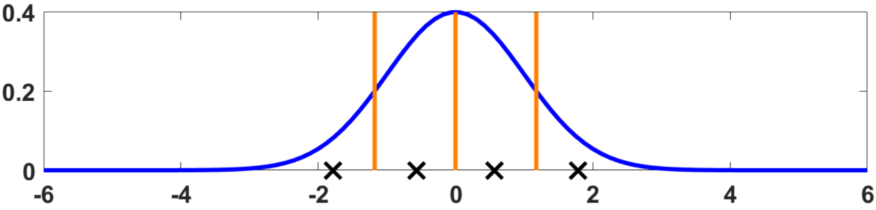

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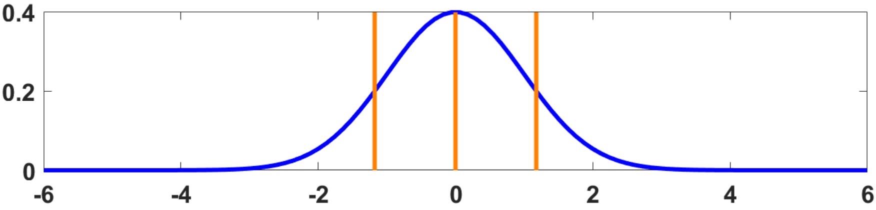

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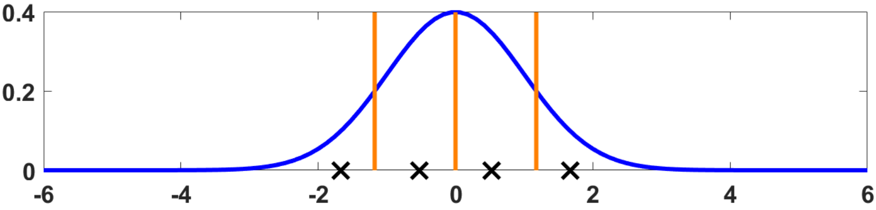

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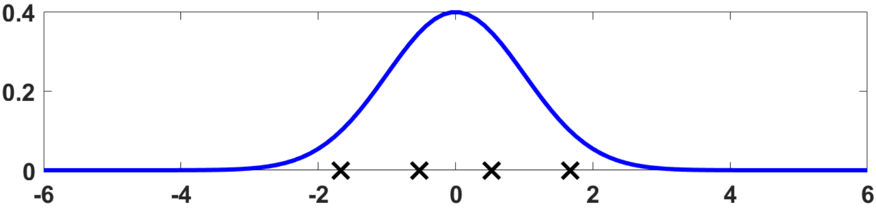

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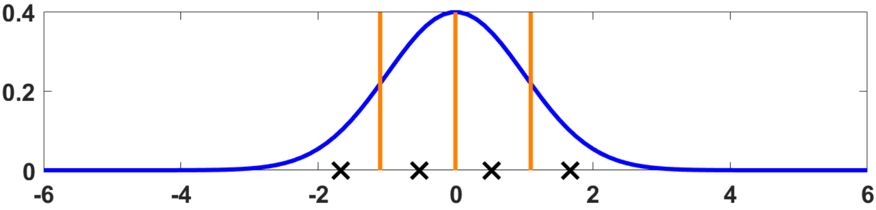

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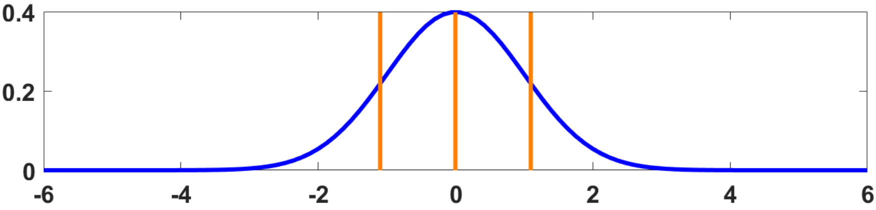

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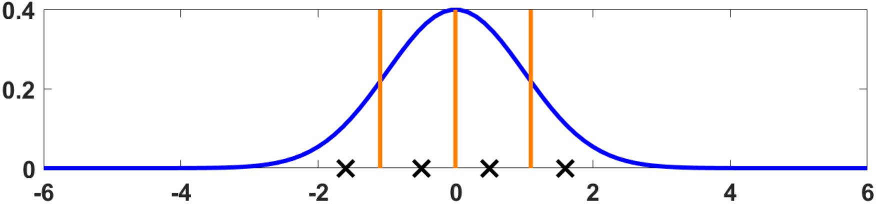

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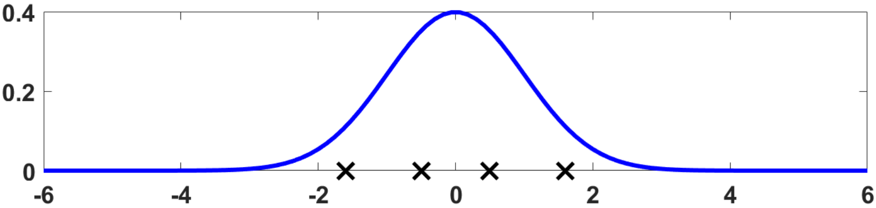

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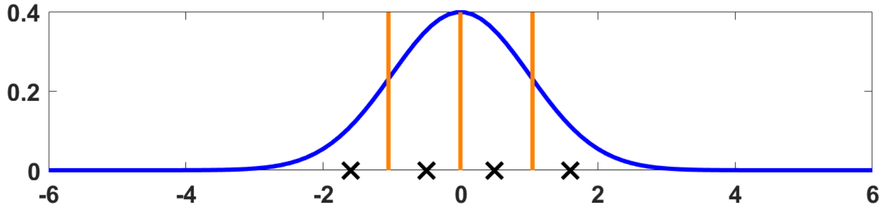

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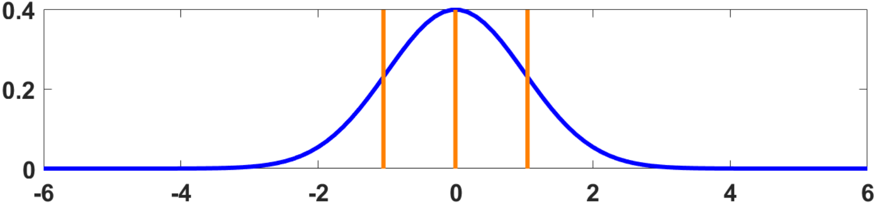

Lloyd-Max Algorithm

Nearest Neighbor: Given reconstruction points, find optimal cells

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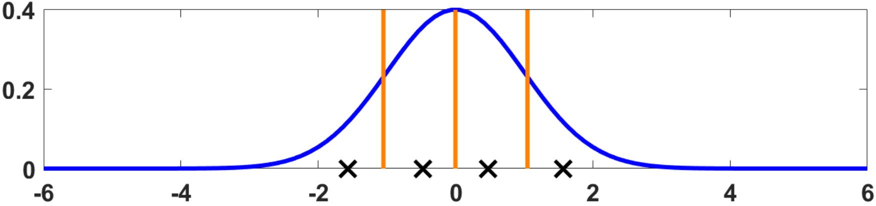

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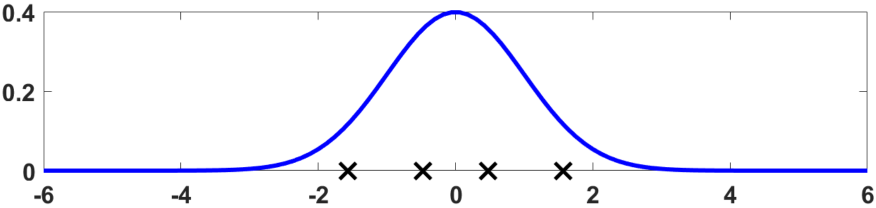

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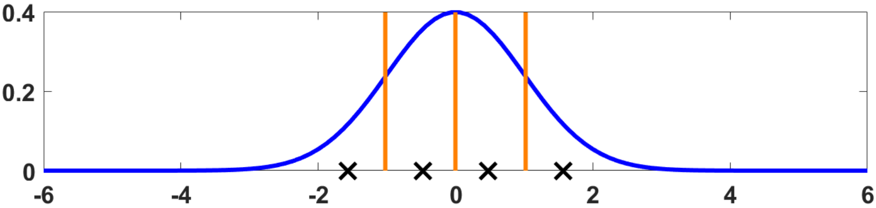

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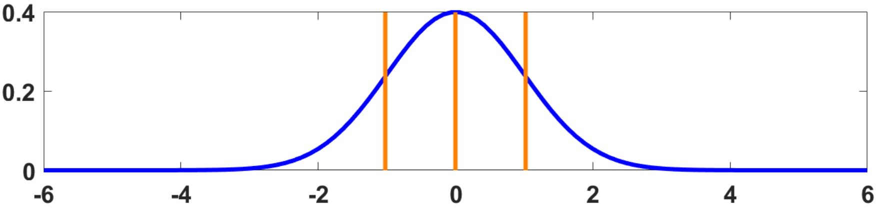

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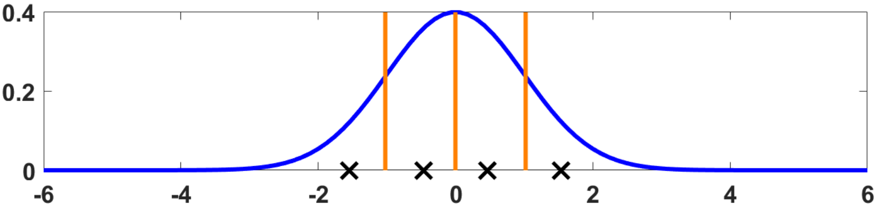

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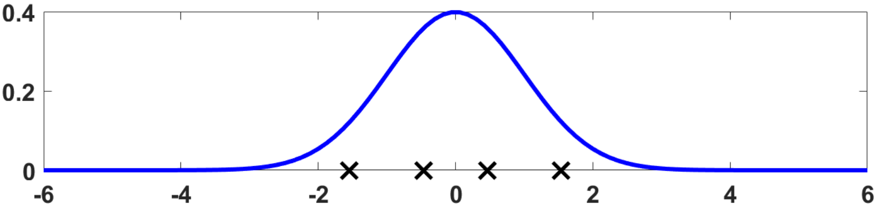

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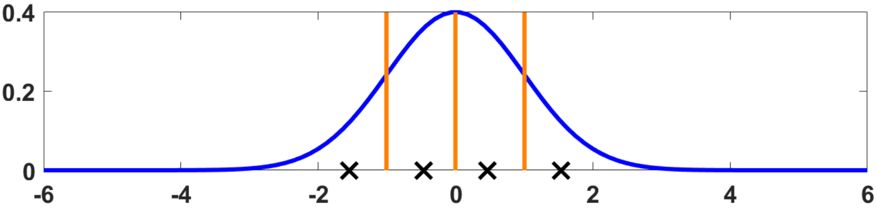

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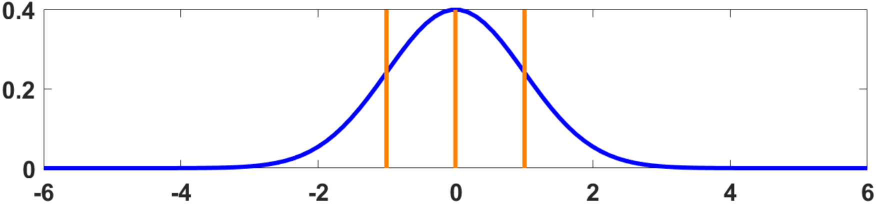

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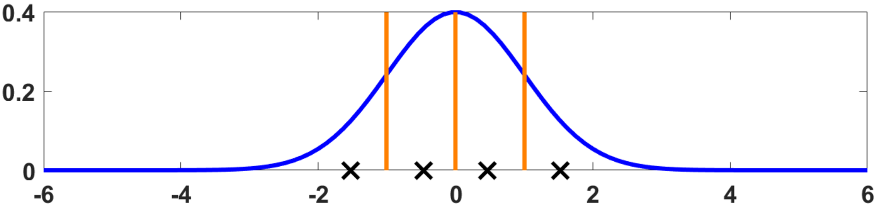

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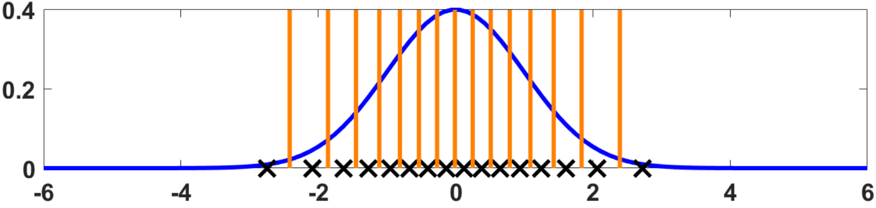
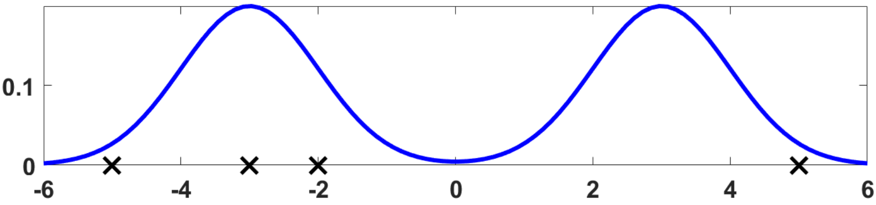


Lloyd-Max Algorithm

- Optimal quantizer necessarily satisfies *Centroid* and *NN*
- But... They are not sufficient in general! ☹
- Lloyd-Max algorithm might converge to a local optimum...



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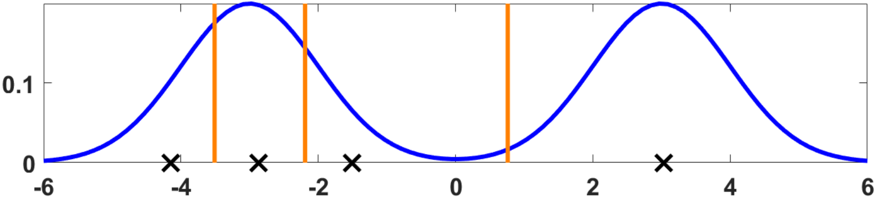


Lloyd-Max Algorithm

When does Lloyd-Max converge to global optimum?
[Fleischer '64][Trushkin IT'82][Kieffer-Jahns-Obuljen IT'88]

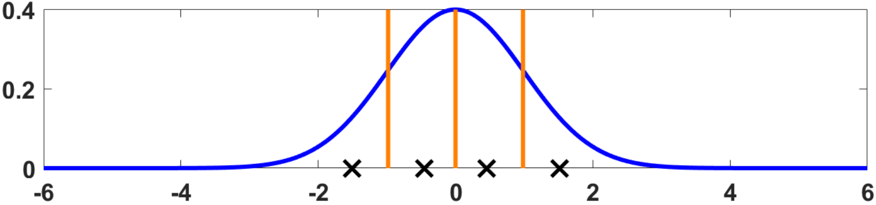
- Conditions for existence of only one local optimum ⇒ **Global**
- **Log-concave** distributions satisfy these conditions
- Important special case: **Gaussian distribution** ☺

- One stage of LQG with finite-rate noiseless channel ✓

What about more stages?

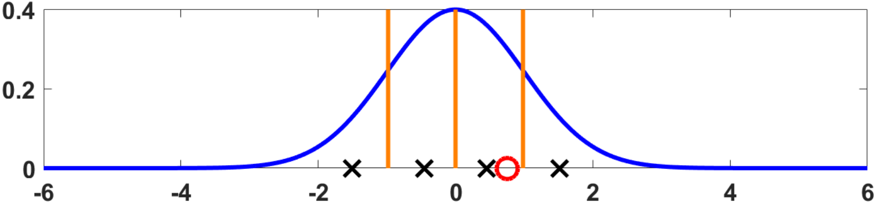
Multi-Stage Control with Finite-Rate Feedback

- First input is Gaussian $\Rightarrow$ Log-concave pdf
- Lloyd-Max quantizer is optimal



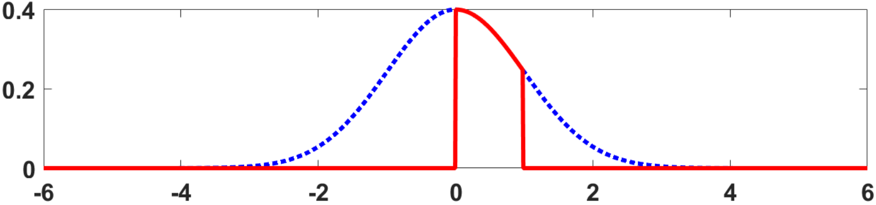
Multi-Stage Control with Finite-Rate Feedback

- First input arrives and chooses cell



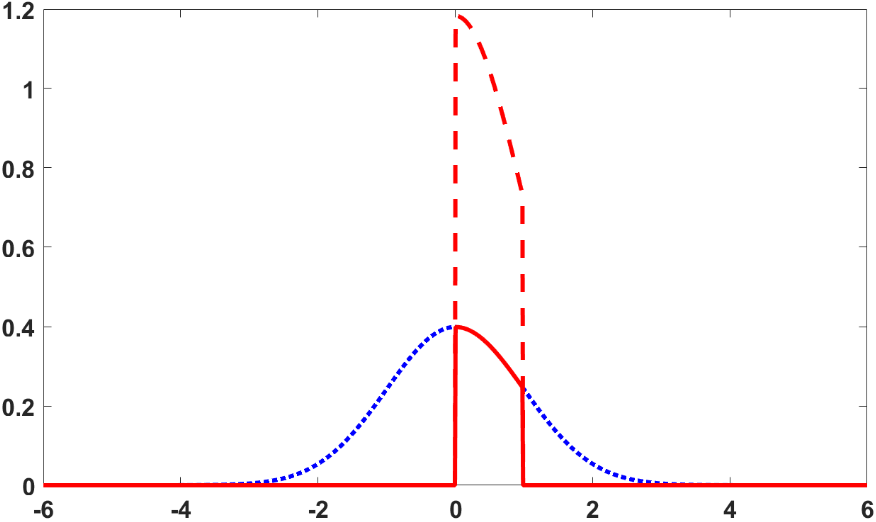
Multi-Stage Control with Finite-Rate Feedback

- Quantization noise ("error") is determined by the hit cell



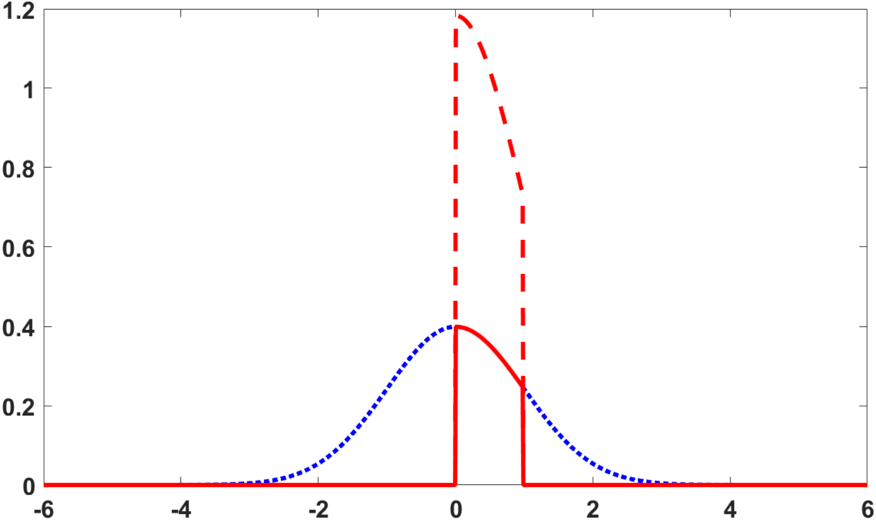
Multi-Stage Control with Finite-Rate Feedback

- Quantization noise pdf = truncated original pdf normalized



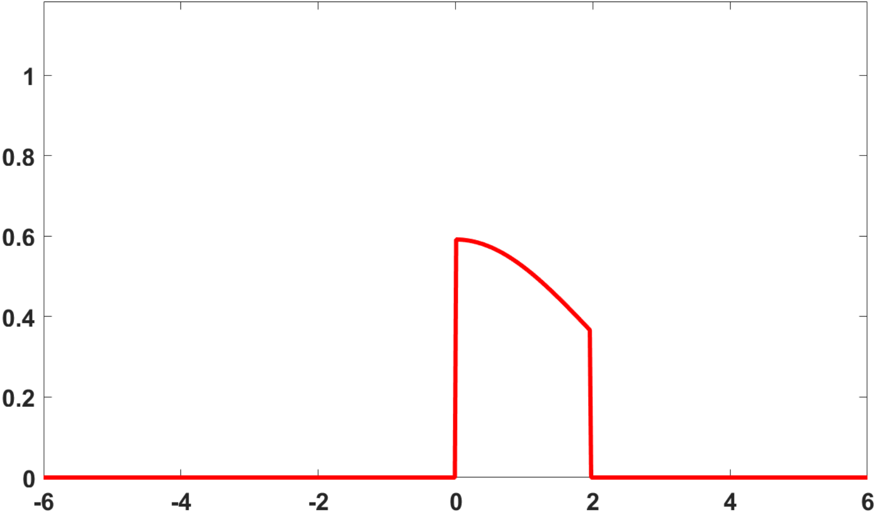
Multi-Stage Control with Finite-Rate Feedback

- Truncated log-concave pdf is **log-concave**!



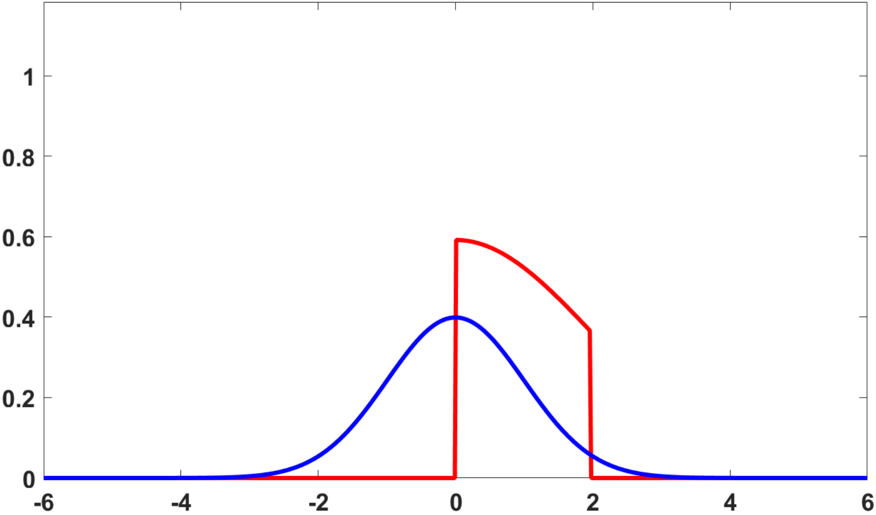
Multi-Stage Control with Finite-Rate Feedback

- Quantization noise is inflated by α (pdf remains log-concave)



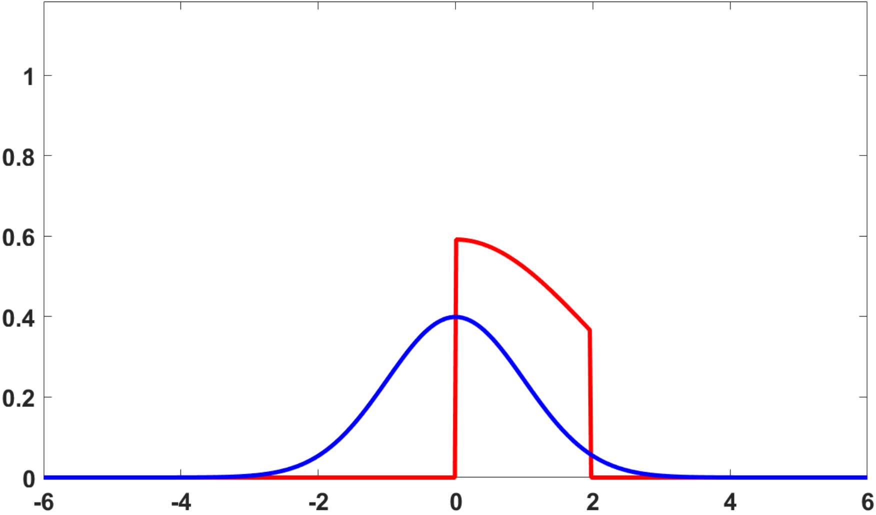
Multi-Stage Control with Finite-Rate Feedback

- Inflated error added to new w_t $\Rightarrow$ Convolution of pdfs



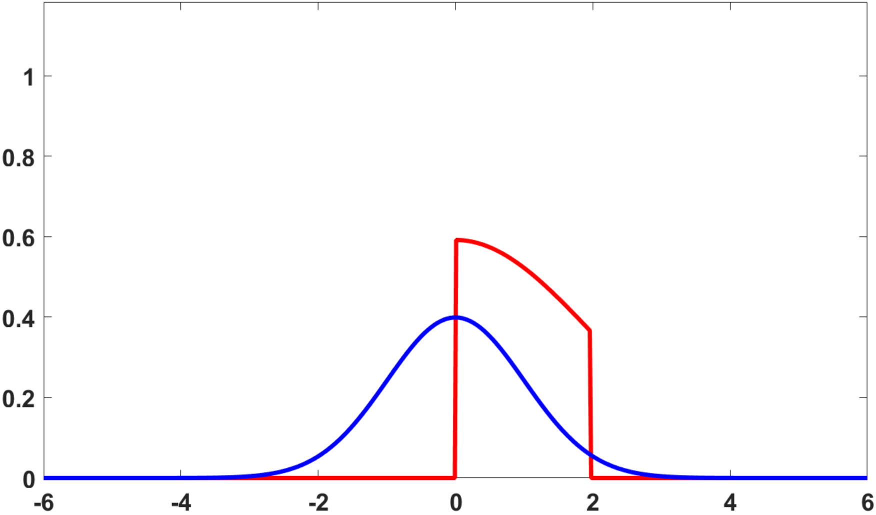
Multi-Stage Control with Finite-Rate Feedback

- $w_t \sim \mathcal{N}(0, W) * \text{log-concave quantization error}$



Multi-Stage Control with Finite-Rate Feedback

- Convolution of log-concave functions is also **log-concave**!



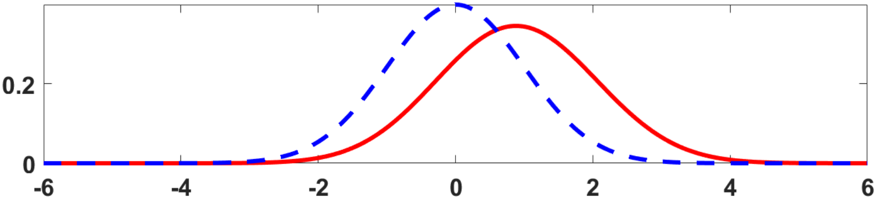
Multi-Stage Control with Finite-Rate Feedback

Resulting pdf (in red)

- Depends on cell index chosen in previous stage(s)
- Log-concave

Applying Lloyd-Max quantization in second stage is optimal!

- First-stage pdf (in blue) for comparison



Optimal Greedy Algorithm

- Lloyd-Max quantization minimizes squared error of that stage
- Lloyd-Max quantization = Optimal **greedy** algorithm
- But... It is not necessarily globally optimal...
- Quantizer used affects pdf of future stages
- Quantizer should be chosen according to the dynamic program

Linear Quadratic Regulator (LQR) Example

- LQR setting with $x_0 \sim \mathcal{N}(0, X)$ and $\alpha = 1$:

$$\begin{cases} x_{t+1} &= x_t + u_t \\ y_t &= x_t \end{cases}$$

- Assume for simplicity we are interested in accumulated MMSE:

$$J = \sum_{t=1}^{T} x_t^2 \triangleq \sum_{t=1}^{T} J_t$$
$$J_t \triangleq x_t^2$$

- In this case, clearly $u_1 = -\hat{x}_0$, $u_2 = -\left(\widehat{x_0 - \hat{x}_0}\right)$
- $\{u_t\}$ sequence refines the reconstruction of x_0 at every stage
- This problem is known in IT as *successive refinement*

Successive Refinement

- Two descriptions of the source x:
  - Description of rate R_1
  - First description of rate R_1 and another description of rate R_2

Successive refinement with encoding/decoding of long blocks [Equitz-Cover IT'91][Rimoldi IT'94]

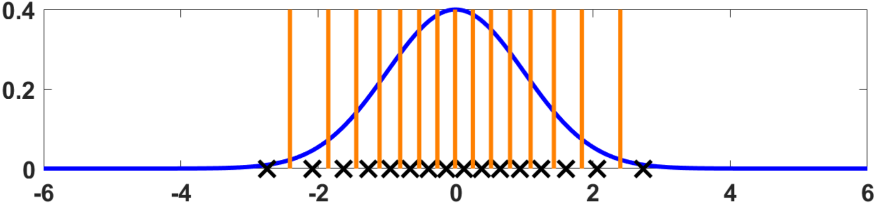
- Optimal trade-off $(R_1, R_2) \leftrightarrow (J_1, J_2)$ is known
- J_2 is the same as if $R_1 + R_2$ was given to begin with (no J_1)

- But... **Optimal scalar quantizer for J_1 is not optimal for J_2**
- Tension between optimizing J_1 and J_2

  $\Rightarrow$ **Suboptimality of Lloyd-Max** in LQR example [Fu AC'12]

Successive Refinement

Lloyd-Max algorithm with $2^R = 16$ quantization points:



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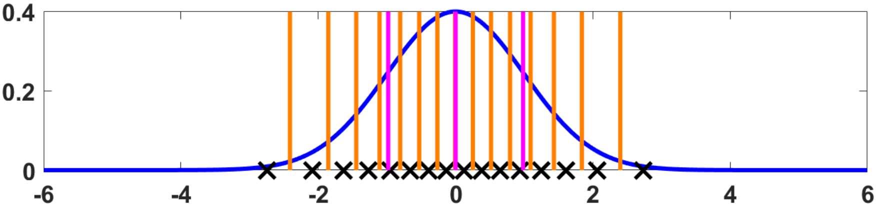
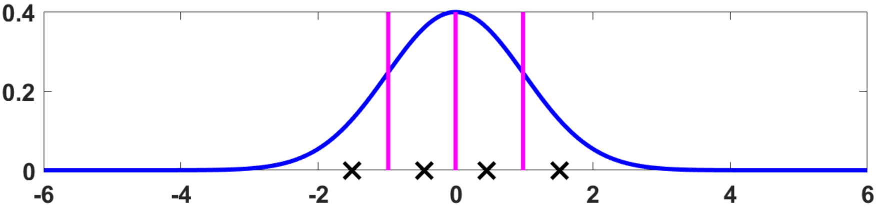


Lloyd-Max algorithm with $2^{R_1} = 4$ quantization points:



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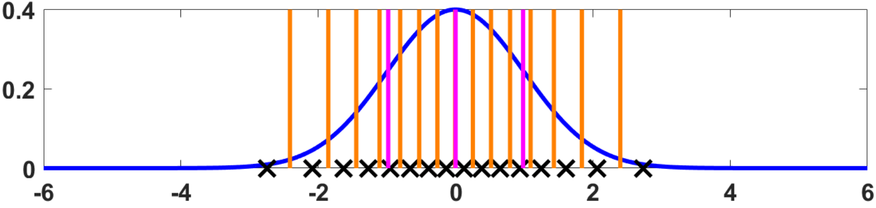
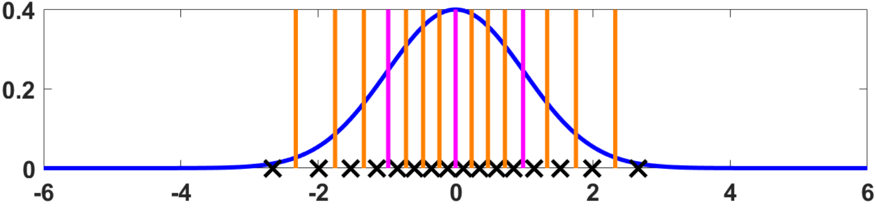


Lloyd-Max algorithm ran for each cell with $2^{R_2} = 4$ points:



Optimal Scalar Successive Refinement

Optimal average-stage MMSE of scalar successive refinement [Dumitrescu-Wu IT'09]

- Generalized Lloyd-Max can be constructed [Brunk-Farvardin '96]
- Converges to **optimal average-stage MMSE**
- Extends Trushkin's conditions to successive refinement setting
- Conditions are satisfied for log-concave pdfs

LQR for $\alpha \neq 1$

- $J = J_1 + \alpha^2 J_2 + \cdots + \alpha^{2(T-1)} J_t$
- Adequate generalized LM algorithm can be constructed
- Converges to optimal weighted MSE J for log-concave pdfs

Future Research: Optimal Quantization for LQG

- We saw how to construct optimal quantizers for LQR
- How to construct optimal quantizers for LQG control?
- Input pdf at every stage is log-concave
- Variant of generalized Lloyd-Max quantization will be optimal
- What variant to use would be dictated by dynamic program
- How to construct a good low-complexity scheme?

Complementary Results

High Resolution: Bennett's (Approx.) Optimal Quantizer

- Assume a large number of points
- Overload noise (noise outside dynamic range) is negligible
- Quantization points "can" be approximated by continuous pdf
- Optimal quantization points distribution $\propto f_X^{1/3}$
- Optimal distortion $= \frac{1}{12N^2} \|f_X\|_{1/3}$
- Under these assumptions, successively refinable
  (no tensions between J_1 and J_2)