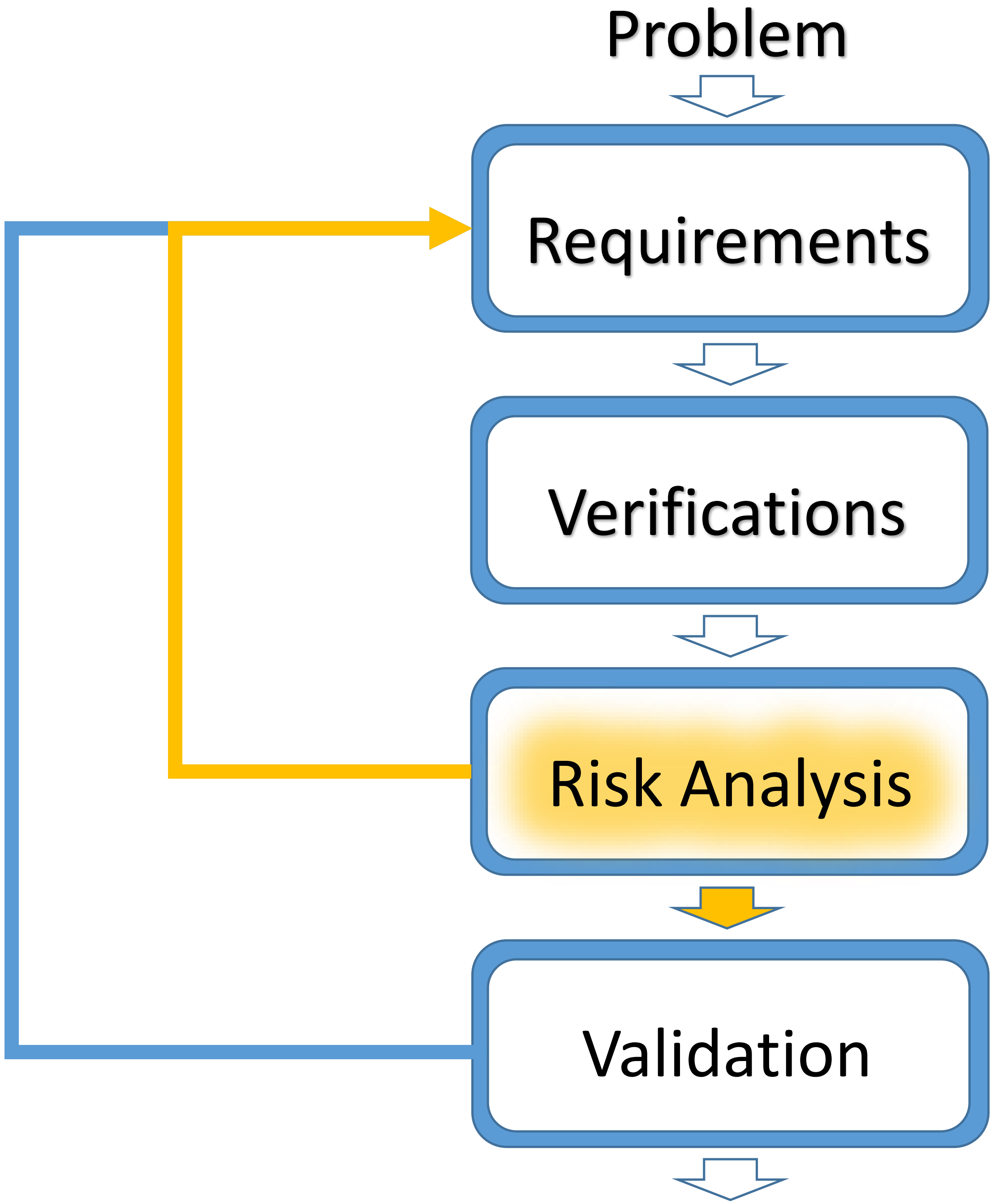
Lecture 7
Tolerance and Risk



Risk and Tolerance Analyses:

The risk of the failure of specific system component is dependent on two variables, the **consequence** of the loss and the **probability** that the loss will occur.

Tolerance Analyses

- What is a tolerance analysis?
  - According to Dieter:

  “ A tolerance is the permissible variation from the specified dimension”

- Why is tolerance important?
  - Parts aren’t uniform (*quality control*), helps you understand whether those variations are going to be problematic.
  - Helps you decide between different parts for the same job.
  - Can affect your cost, reliability, quality of your design.
  - With mechanical design, helps you determine *fit* and *tolerance stackup*

From Dieter and Schmidt 2013

How do we express tolerances?

- Bilateral tolerance
  - Balanced bilateral
  - Unbalanced bilateral
- Unilateral tolerance
- Don’t forget to specify whether bounds are inclusive

From Dieter and Schmidt 2013

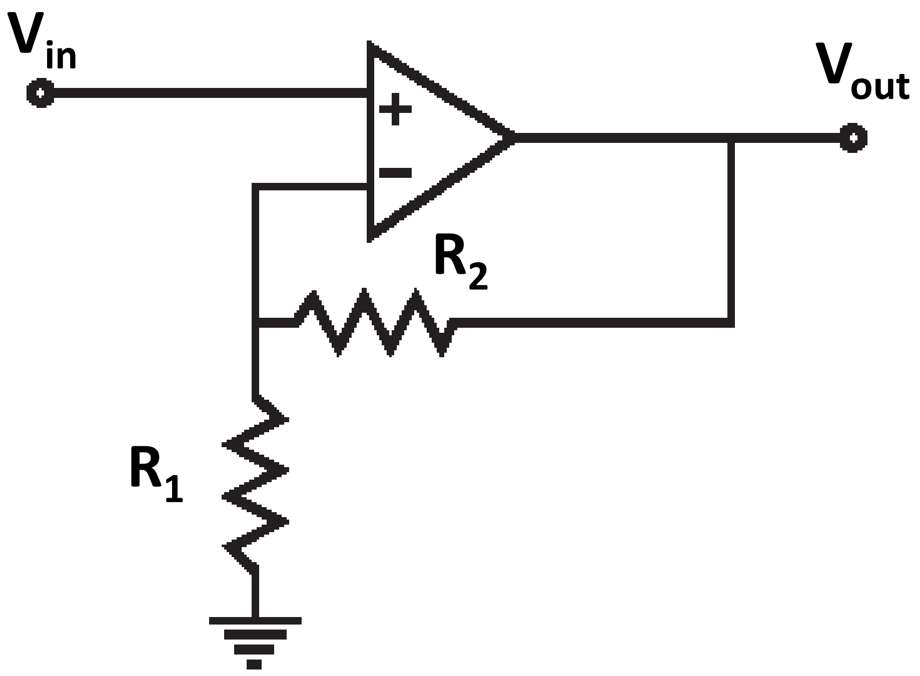
Tolerance analyses on components

- We will discuss two methods:
  - Extreme value analysis
    - Vary components to find extreme values of circuit performance.
  - Monte Carlo
    - Randomly sample components and calculate expected performance.

http://robustdesignconcepts.com/files/LM117/files/Tolerance_Methods.pdf

Tolerance Analysis: Simple Example

- Consider that we want to construct a non-inverting amplifier with a gain of 3±0.1.

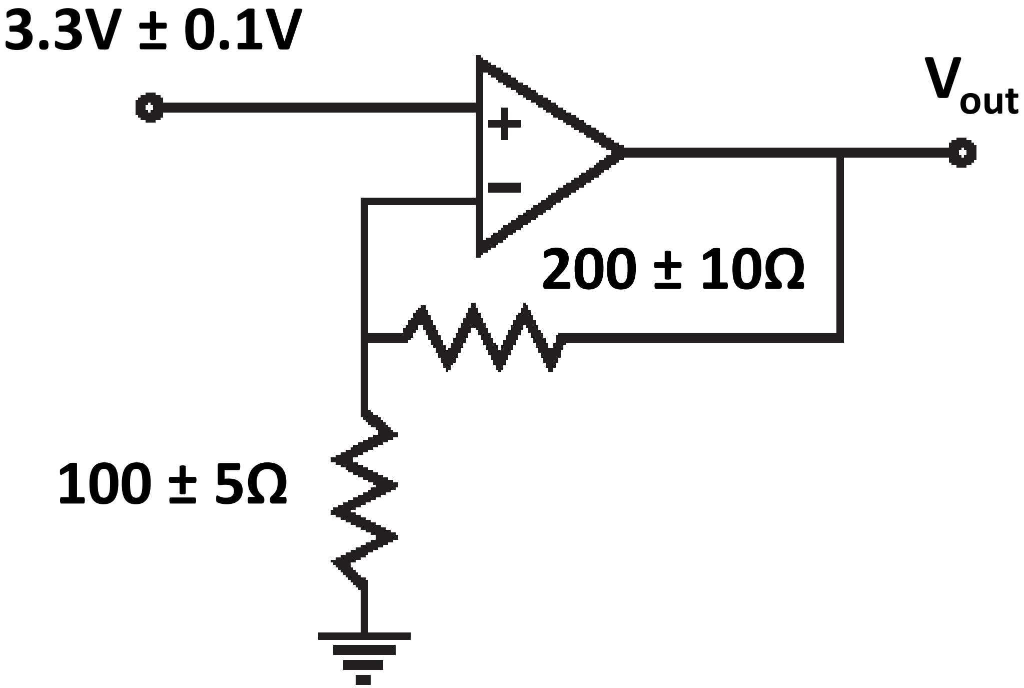


- Let's assume that we have a voltage input of 3.3V ± 0.1V.
- We know that the voltage at the output (assuming an ideal op amp) is defined as:

$$V_{out} = V_{in}\,(1 + R_2/R_1)$$

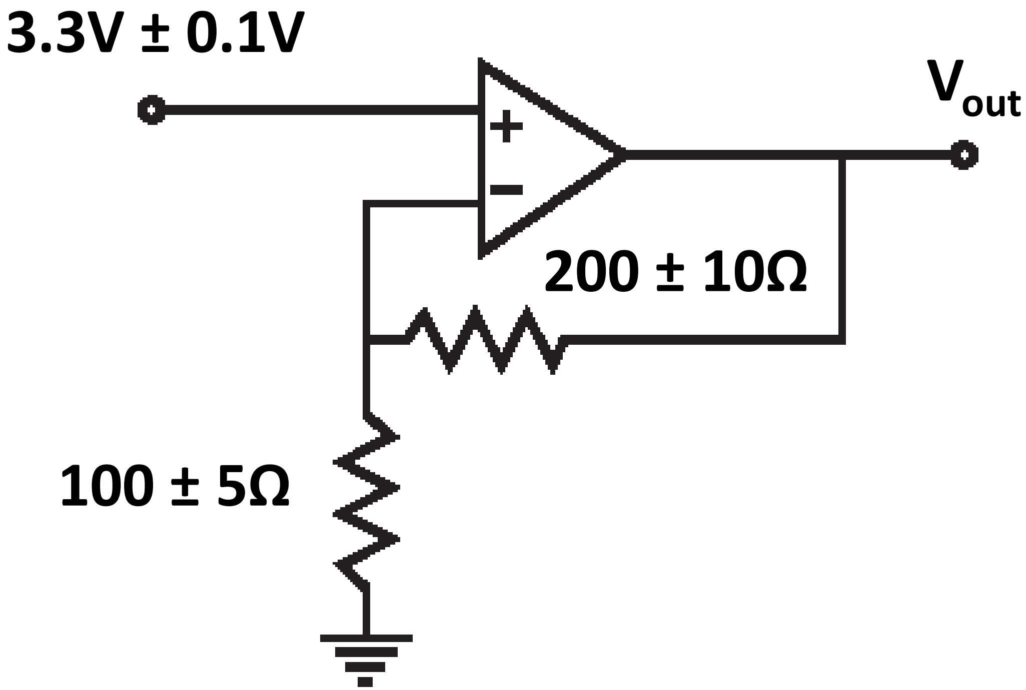
Tolerance Analysis: extreme value analysis

- Let's say that we choose to use a 200Ω for R_2 and a 100Ω for R_1. Let's also assume that we use cheap 5% resistors.



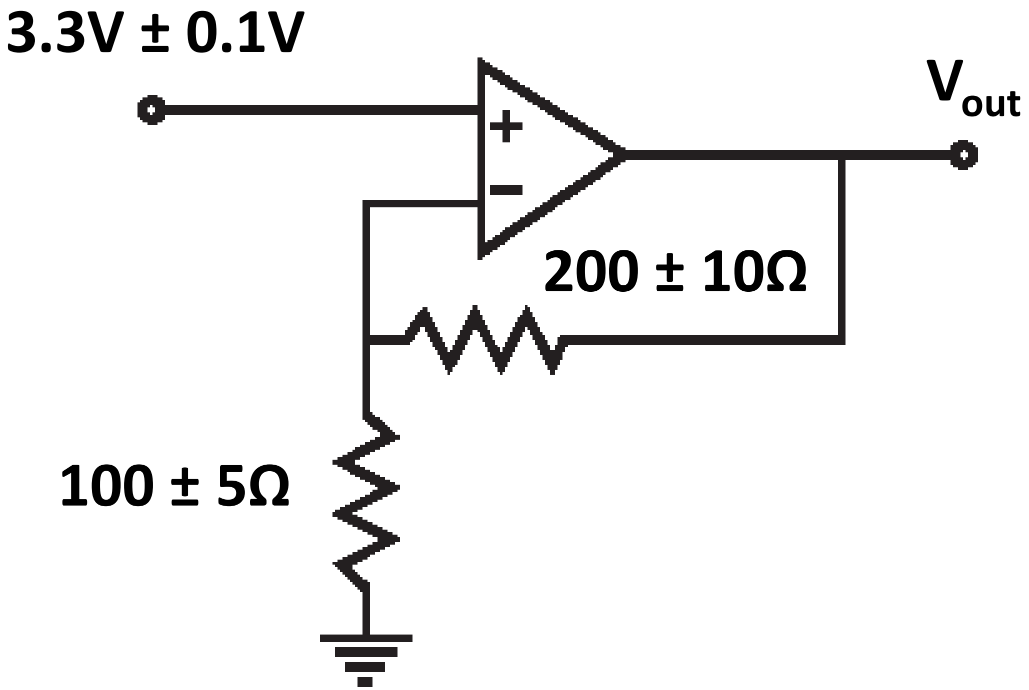
Let's set up an analysis matrix. We will calculate the voltage outputs for all of the possible combinations of components.

Tolerance Analysis: extreme value analysis



V_{in}	R_1 (Ω)	R_2 (Ω)	V_{out}	Gain
3.3	95	190	9.9	3
3.3	95	210	10.59	3.21
3.3	105	190	9.27	2.81
3.3	105	210	9.9	3

Tolerance Analysis: extreme value analysis



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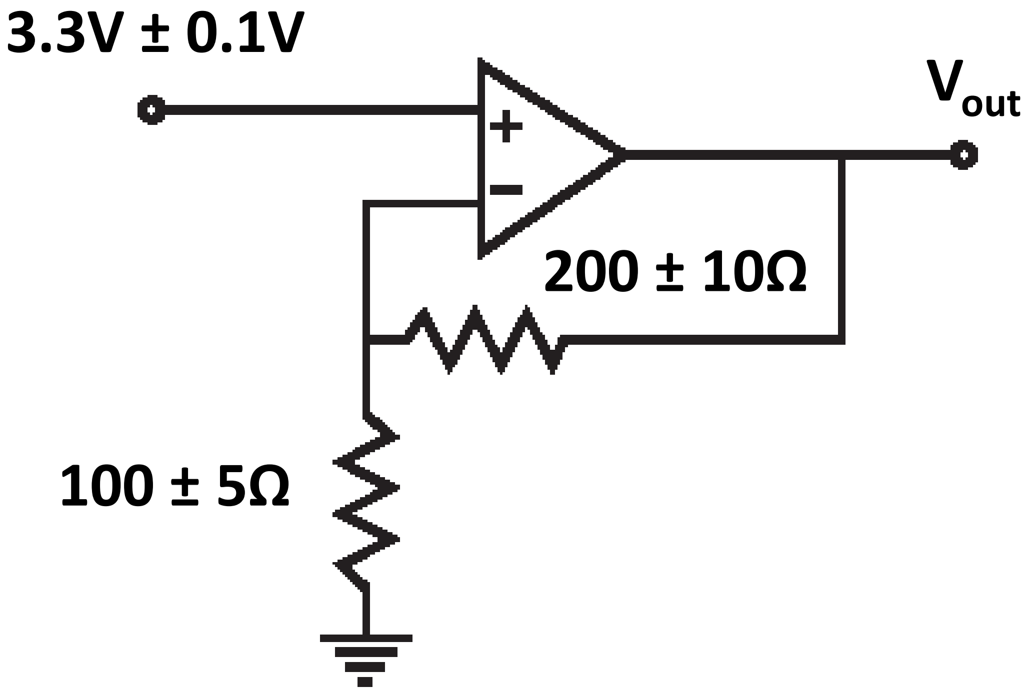
Tolerance Analysis: adjust

Let's repeat the analysis with 1% resistors.



V_{in}	R_1 (Ω)	R_2 (Ω)	V_{out}	Gain
3.3	99	198	9.9	3
3.3	99	202	10.03	3.04
3.3	101	198	9.77	2.96
3.3	101	202	9.9	3

Tolerance analyses on components

- What if cost is an issue?
  Low tolerance parts are often MUCH more expensive.
- What if you want to know how likely a circuit is to meet tolerance?
- What if you want to account for fact that a tolerance value does not specify how likely a specific value will be?
- What if the circuit is very complicated?

http://robustdesignconcepts.com/files/LM117/files/Tolerance_Methods.pdf

Monte Carlo Analysis

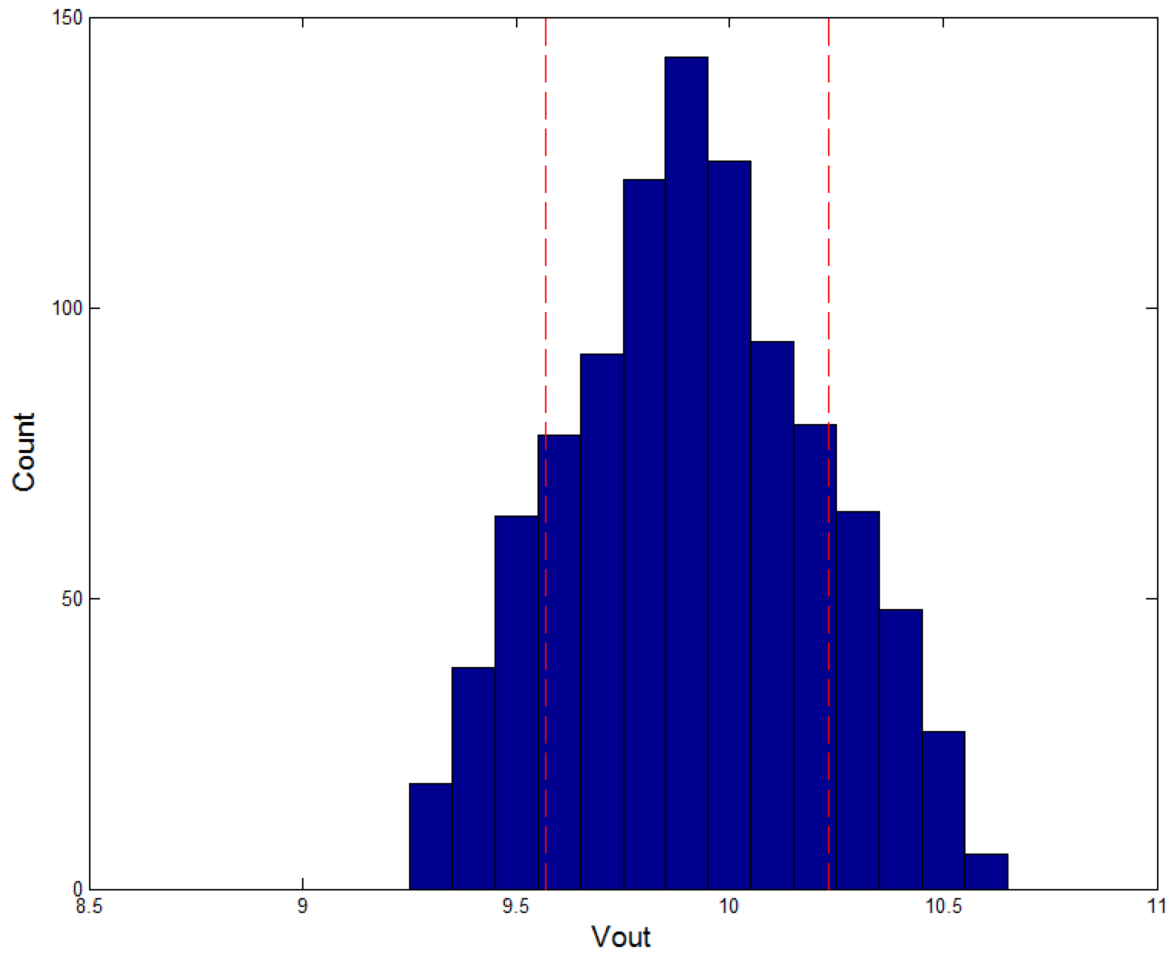
- In these cases, you can use a Monte Carlo analysis.
  - Set up circuit in simulator or build test circuit.
  - Randomly select your components from a large potential pool.
  - Analyze results statistically.

http://robustdesignconcepts.com/files/LM117/files/Tolerance_Methods.pdf

Monte Carlo Analysis

- MATLAB
- 1000 iterations
- Assume values of components follow a distribution.

- Here we assume uniform distribution.

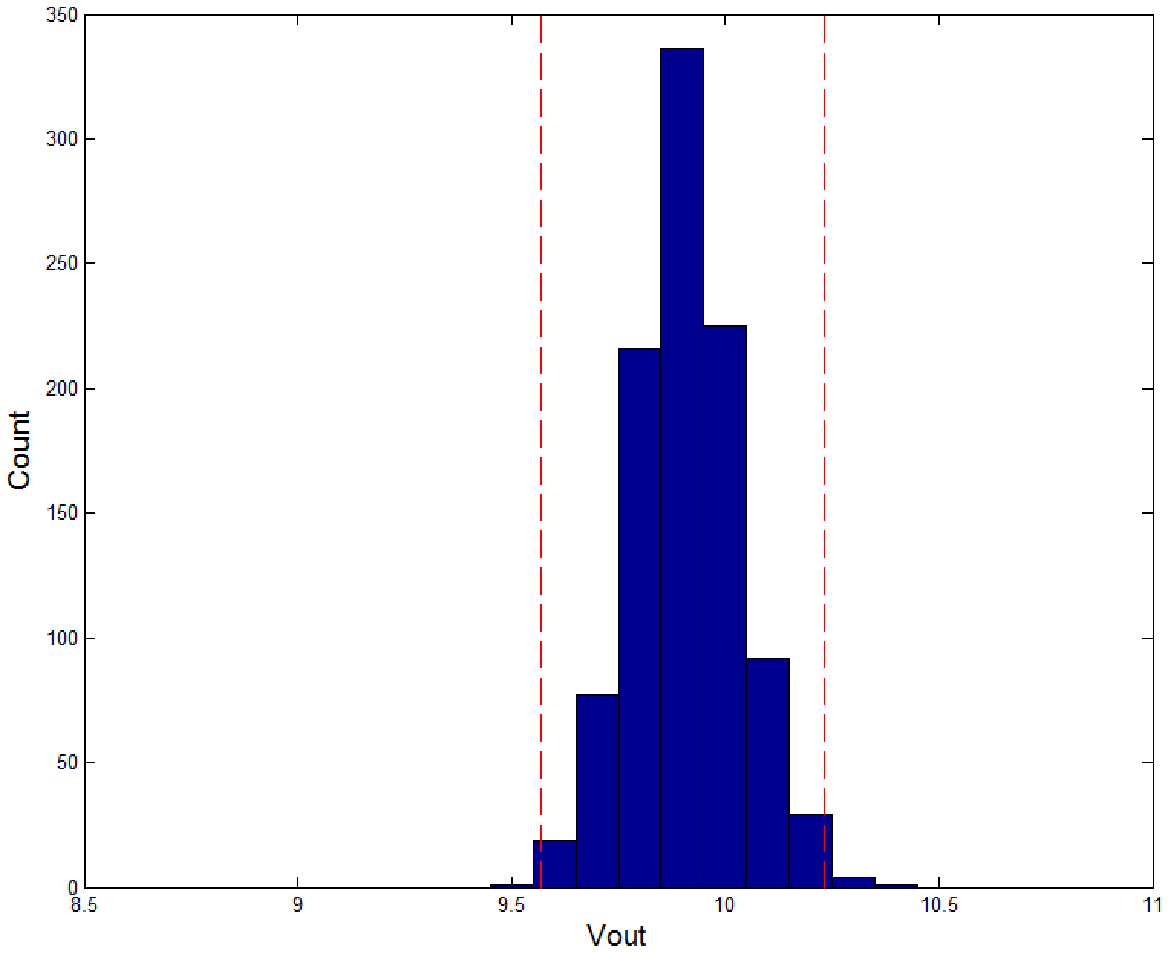


Uniform distribution

Monte Carlo Analysis

- MATLAB
- 1000 iterations
- Assume values of components follow a distribution.

- What if component values follow a normal distribution and tolerance is representative of 3 * standard deviation?



Normal distribution

Tolerance Analysis: filter example

Example:
https://courses.engr.illinois.edu/ece445/documents/tolerance-analysis-guide.pdf

- Large construction projects frequently generate ground vibrations, which result from moving heavy equipment and driving piles.
- Our project is a tool for construction companies to monitor the level of vibrations which propagate off the construction site.
- We decide that the highest risk component is the anti-aliasing filter before A/D conversion. If aliased frequencies are allowed to pass, sensor may give inaccurate information (high Loss).

Tolerance Analysis: Example

There are two requirements for the filter:

1) The flatness of the passband from 0-100 Hz must be less than 1dB.
2) It must have an attenuation of at least 3 dB for frequencies at or above the Nyquist frequency.

To achieve the three requirements listed in the previous paragraph, a 10 kΩ resistor with 1% tolerance and a 62 nF capacitor with 6% tolerance were chosen. The sampling rate is 400Hz.

Tolerance Analysis: Hypothetical Example

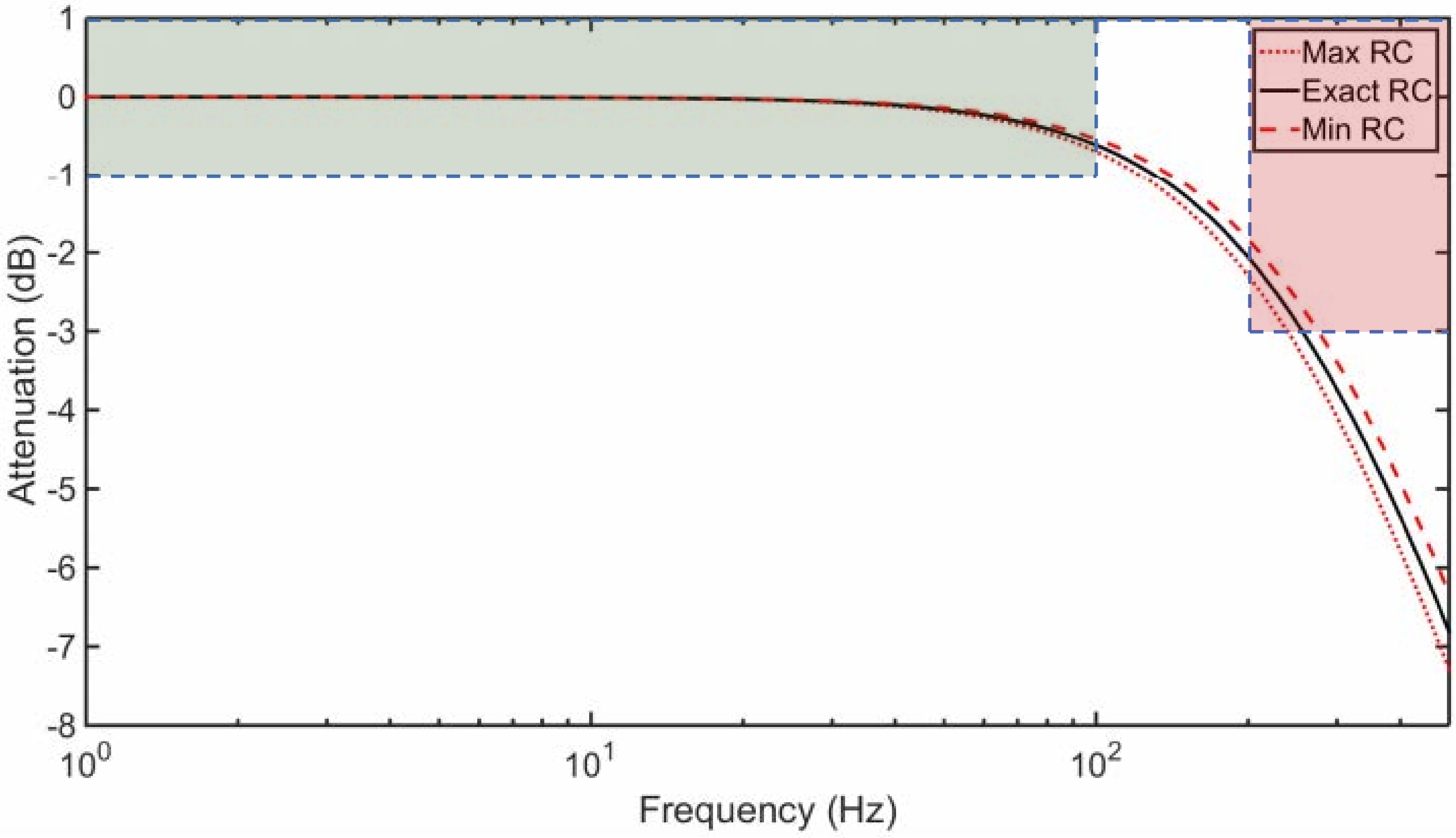
Plot our best, exact, and worst case RC products.

Requirement 1

- It can be seen that the flatness of the passband from 0-100Hz is less than 1db.

Requirement 2

- The attenuation at 200Hz (Nyquist frequency) is **less than** 3db.



Tolerance Analysis: Hypothetical Example

Plot our best, exact, and worst case RC products.

Requirement 1

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Requirement 2

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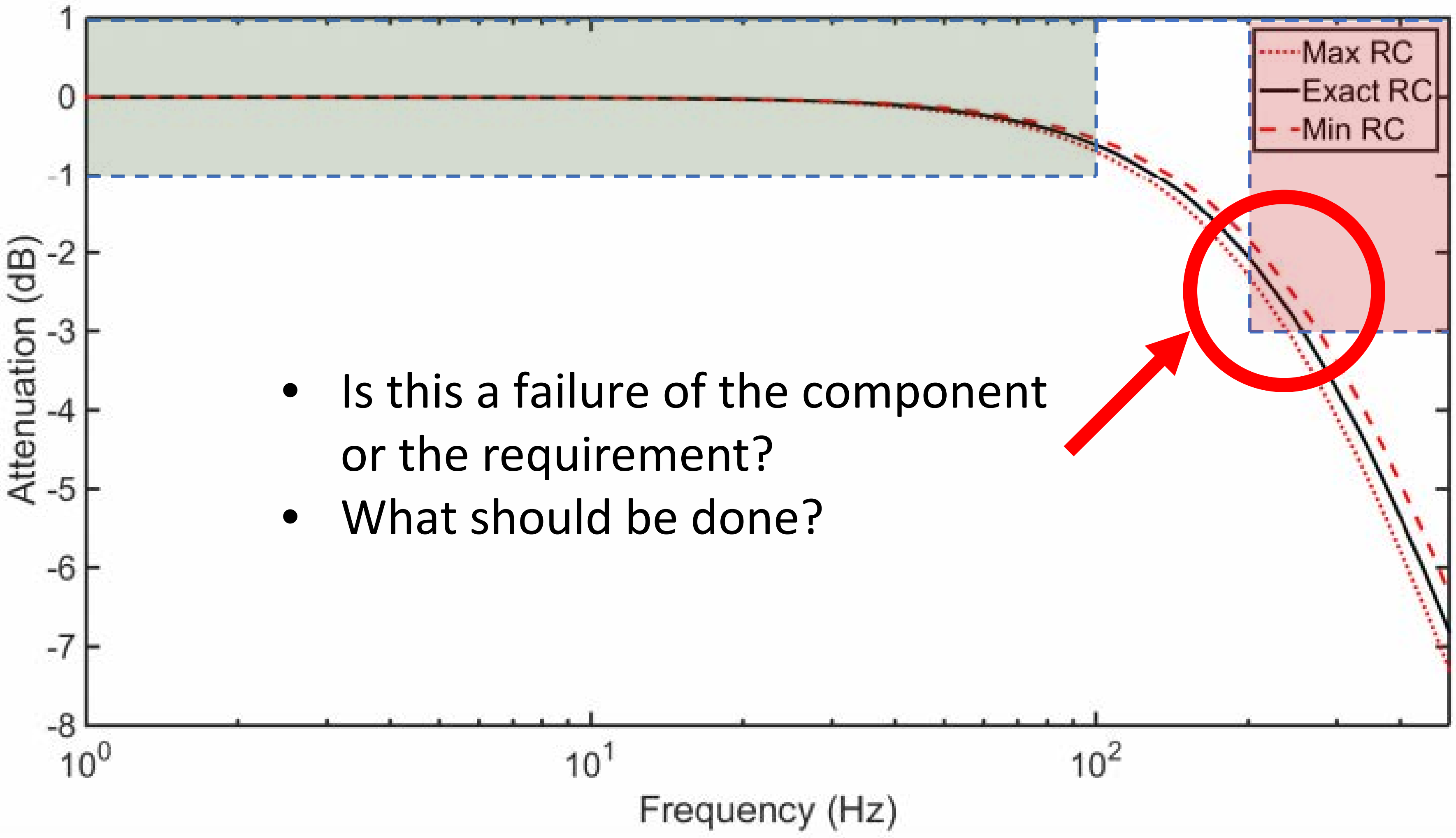

- Is this a failure of the component or the requirement?
- What should be done?

Hazard?

From Dieter and Schmidt 2013

https://en.wikipedia.org/wiki/Lightning_strike#/media/File:Lightning_striking_the_Eiffel_Tower_-_NOAA.jpg

What is risk?

- Circumstances once thought to be acceptable.
- Abnormal operation not predicted at design.

https://engineering.purdue.edu/VRSS/sorenson_research.html

From Dieter and Schmidt 2013

TABLE 14.1
Classification of Societal Hazards

Category of Hazard	Examples
1. Infections and degenerative diseases	Influenza, heart disease, AIDS
2. Natural disasters	Earthquakes, floods, hurricanes
3. Failure of large technological systems	Failure of dams, power plants, aircraft, ships, buildings
4. Discrete small-scale accidents	Automotive accidents, power tools, consumer and sport goods
5. Low-level, delayed-effect hazards	Asbestos, PCB, microwave radiation, noise
6. Sociopolitical disruption	Terrorism, nuclear weapons proliferation, oil embargo

From W. W. Lawrance, in R. C. Schwing and W. A. Albus (eds.), *Social Risk Assessment*, Plenum Press, New York, 1980.

From Dieter and Schmidt 2013

What is an acceptable risk?

3 Factors involved in acceptable risk

1. Control
2. Size of event
3. Familiarity

From Dieter and Schmidt 2013

http://er.jsc.nasa.gov/seh/pg5.htm

Risk Assessment

$$\boldsymbol{Risk = Loss \ * P}(Loss)$$

- The riskiest component is not simply the one that has the highest chance to fail.
- The riskiest component is the one with the highest **product** of chance of failure multiplied by the consequence of that failure.

What is loss?

- Many ways that there can be loss.
- Many ways things can be a risk.
- Many ways things can be a cost.
- There is not a single way to quantify loss, can be considered in terms of:
  - dollars,
  - reputation,
  - lives,
  - identity,
  - cleanup

New York – workers' compensation

Quantifying Loss

- Quantifying to un-quantifiable:
  - Convert everything to money.
    - For example: courts have standard payouts for many losses.
- Work with actuaries
- The truth is, it is very difficult, try to simplify:
  - Point scale.

HOW MUCH IS A SCHEDULE LOSS OF USE AWARD?

The law states how many benefit weeks you'll receive. It's based on the body part and how much it was damaged. You'll get a certain number of weeks of payment to make up for the permanent injury. For example:

1. The law allows 312 weeks for an arm injury.
2. You lost 25% weeks of the use of your arm.
3. 25% of 312 weeks = 78 weeks.
4. You earn $900 weekly. Two-thirds your average weekly wage (your workers' compensation rate) is $600.
5. $600 a week for 78 weeks = $46,800 to you.

Maximum Possible Compensation

Member Lost	Weeks of Compensation
Arm	312
Leg	288
Hand	244
Foot	205
Eye	160
Thumb	75
First Finger	46
Second Finger	30
Third Finger	25
Fourth Finger	15
Great Toe	38
Other Toe	16

http://www.wcb.ny.gov/content/main/Workers/ScheduledLossUse.jsp

Quantifying Loss

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Ranking	Effect	Criteria: Severity of Effect
1	None	No effect
2	Very Minor	Very minor effect on product or system performance.
3	Minor	Minor effect on product or system performance.
4	Low	Small effect on product performance. The product does not require repair.
5	Moderate	Moderate effect on product performance. The product requires repair.
6	Significant	Product performance is degraded. Comfort or convenience functions may not operate.
7	Major	Product performance is severely affected but functions. The system may not be operable.
8	Extreme	Product is inoperable with loss of primary function. The system is inoperable.
9	Serious	Failure involves hazardous outcomes and/ or noncompliance with govt. regulations or standards.
10	Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with govt. regulations.

Probability of Loss

- Can be further broken down into:
  - P(Occurrence), and
  - P(Detection)
- Quantification:
  - statistical studies,
  - actuarial tables
- Simplify:
  - Grading system, another four point scale

Period Life Table, 2013

	Male		
Exact age	Death probability [a]	Number of lives [b]	Life expectancy
0	0.006519	100,000	76.28
1	0.000462	99,348	75.78
2	0.000291	99,302	74.82
3	0.000209	99,273	73.84
4	0.000176	99,252	72.85
5	0.000159	99,235	71.87
6	0.000146	99,219	70.88
7	0.000133	99,205	69.89
8	0.000118	99,192	68.90
9	0.000102	99,180	67.90
10	0.000091	99,170	66.91
11	0.000096	99,161	65.92
12	0.000128	99,151	64.92
13	0.000195	99,138	63.93
14	0.000288	99,119	62.94
15	0.000389	99,091	61.96
16	0.000492	99,052	60.99

https://www.ssa.gov/oact/STATS/table4c6.html

P(occurrence)

- How likely is this failure to occur?
- Example – Improperly installed cam on landing gear.

http://www.airlinesafety.com/editorials/JetBlueLAX.htm

P(detection)

- What is probability that anyone will notice?
- Can be acceptable under certain circumstances.
- Not the same as covering something up.

http://www.airlinesafety.com/editorials/JetBlueLAX.htm

Acceptable Risk

- Dependent on use case, big risk is acceptable in some instances:
  - Treatment of late stage cancer
  - Being the first to walk on the moon
- For whatever scale being used, there will be a threshold.
- If risk is below this threshold, it is acceptable.

Acceptable Risk - Regulation

- In many countries, If risk is high enough, laws are enacted to set what is acceptable.
- Examples of US regulatory agencies?

From Dieter and Schmidt 2013

Failure Mode and Effects Analysis (FMEA)

- Iterate through requirements and ask this question:

"What if we fail this requirement?"

http://www.riskid.nl/en/30-riskid

What if we fail this requirement?

- Failure mode - how will failure occur?
- Consequences
  - What are the effects of this failure?
  - Quantified as a loss.
- Probability of occurrence
  - Second part of risk score
- Will we detect this failure?
- Is this risk of failure acceptable?

http://www.riskid.nl/en/30-riskid

Failure Modes

- How can this requirement fail?
- What happens if we fail this requirement?

Requirement	Failure Mode	Consequence(s) of failure mode
Range must be at least 4 miles.	Range is close to 4 miles	
	Range is over 4 miles	
	Range is far less than 4 miles	

Example: Autonomous Quadcopter for Photography

- Performance
  - Must produce at least twice as much thrust as weight
- Range
  - Travel range of > 4 miles
  - Range must include 2 minutes of loiter time over target.
  - Range must include 10% reserve for emergencies.
- Camera
  - Acquires images at >= 60fps
  - Resolution must exceed 3000 x 2000 pixels
- Navigation
  - Must be accurate to 1m

Example: Autonomous Quadcopter for Photography

http://www.machinerylubrication.com/Read/29346/machinery-criticality-analysis

Mitigation

- If risk is greater than threshold, something must be done.

Risk Mitigation!

- Example – electric socket
- Following mitigation, risk is then rescored.
- Must get score under acceptable risk threshold before moving on.

One more complicating factor: benefits

- The benefit of what you are doing should weigh on your threshold
- Example - Food distribution