

# Screen Gleaning

Receiving and Interpreting Pixels by  
Eavesdropping on Video Signals without a  
Line of Sight

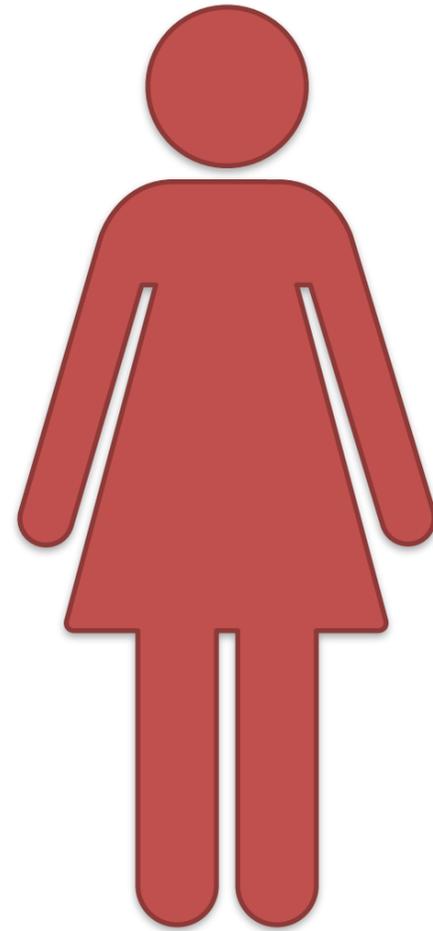
February 25<sup>th</sup>, 2021

Dirk Lauret, Zhuoran Liu and Léo Weissbart

LASER 2021

# Imagine...

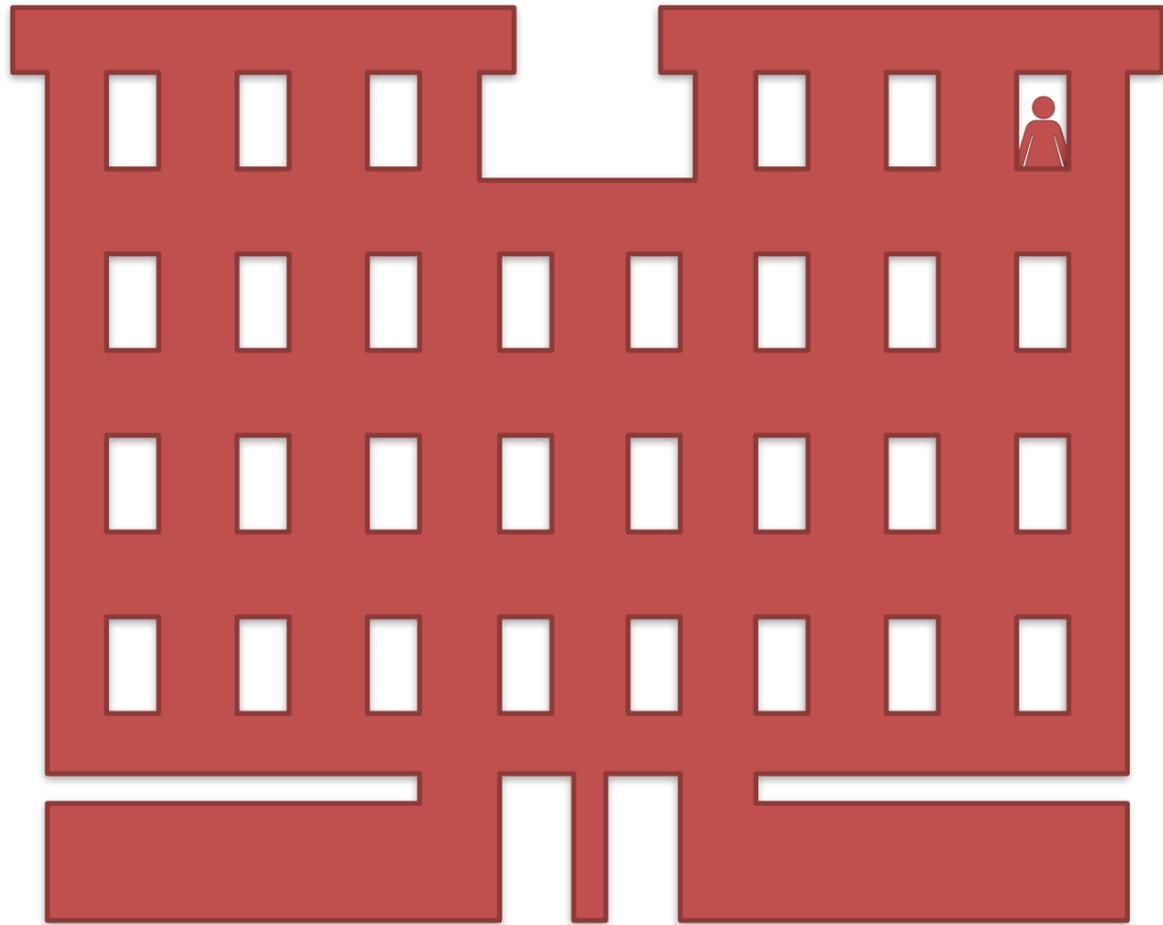
# Imagine...



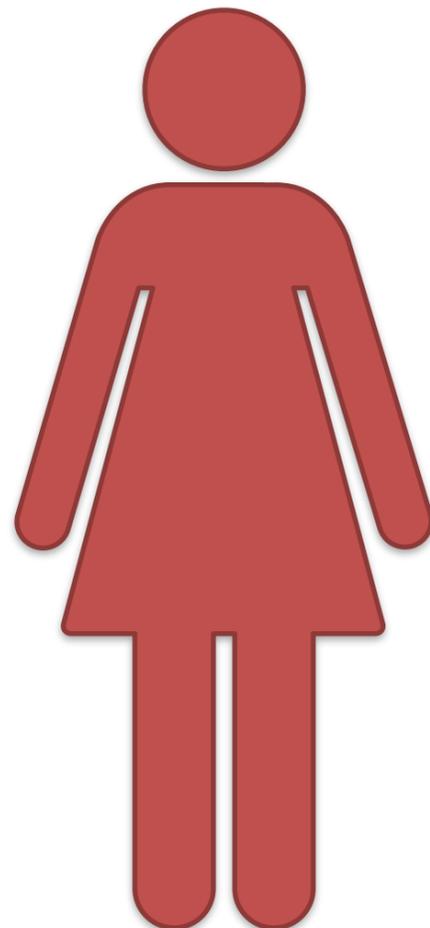
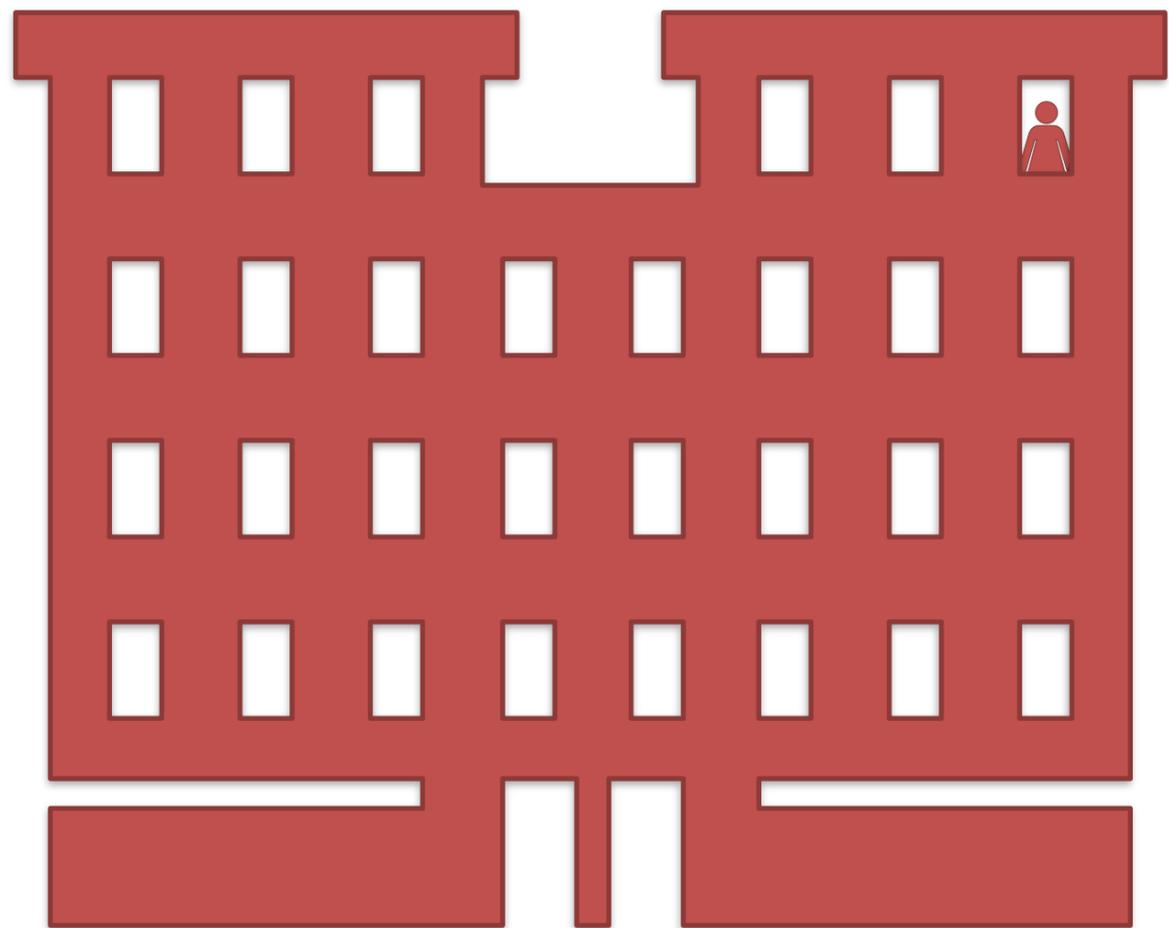
# Imagine...



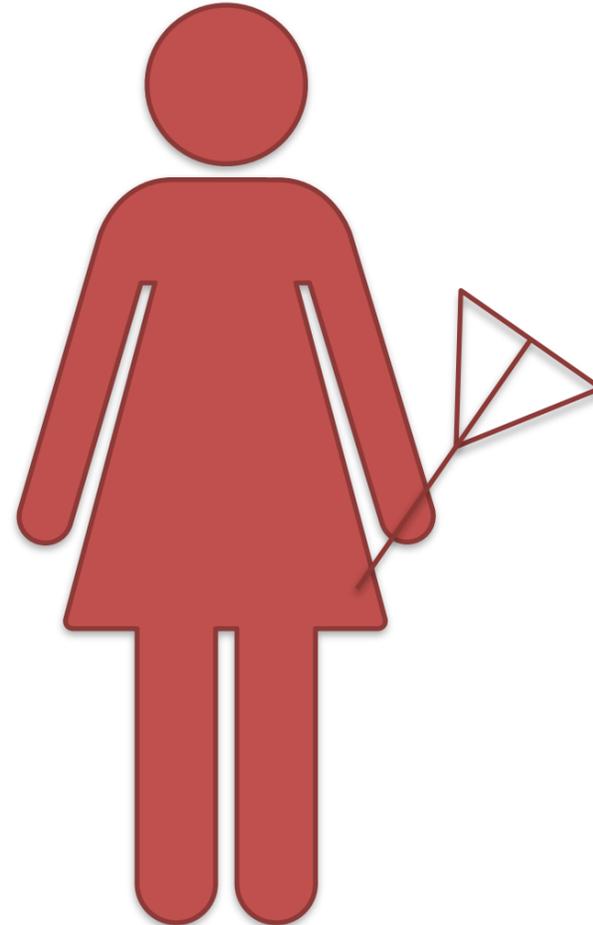
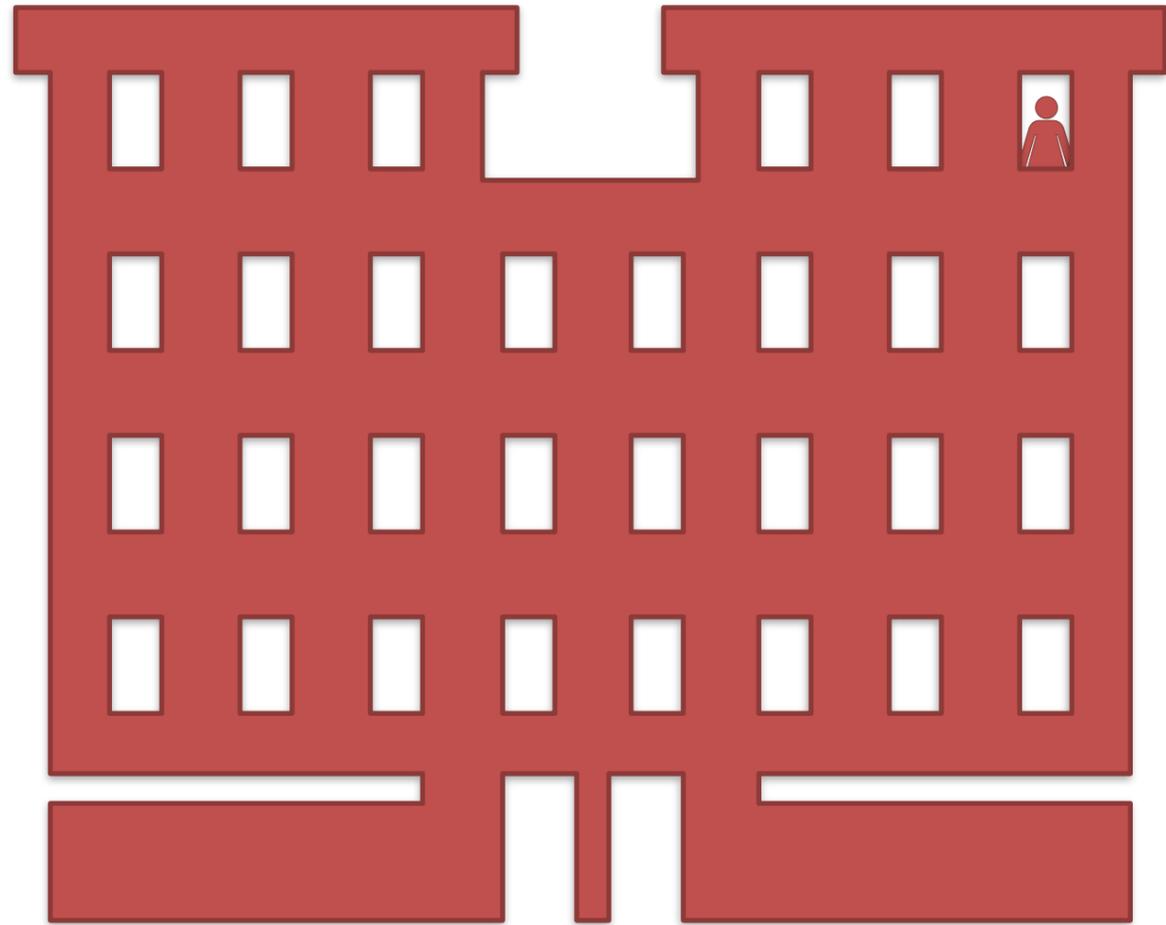
# Imagine...



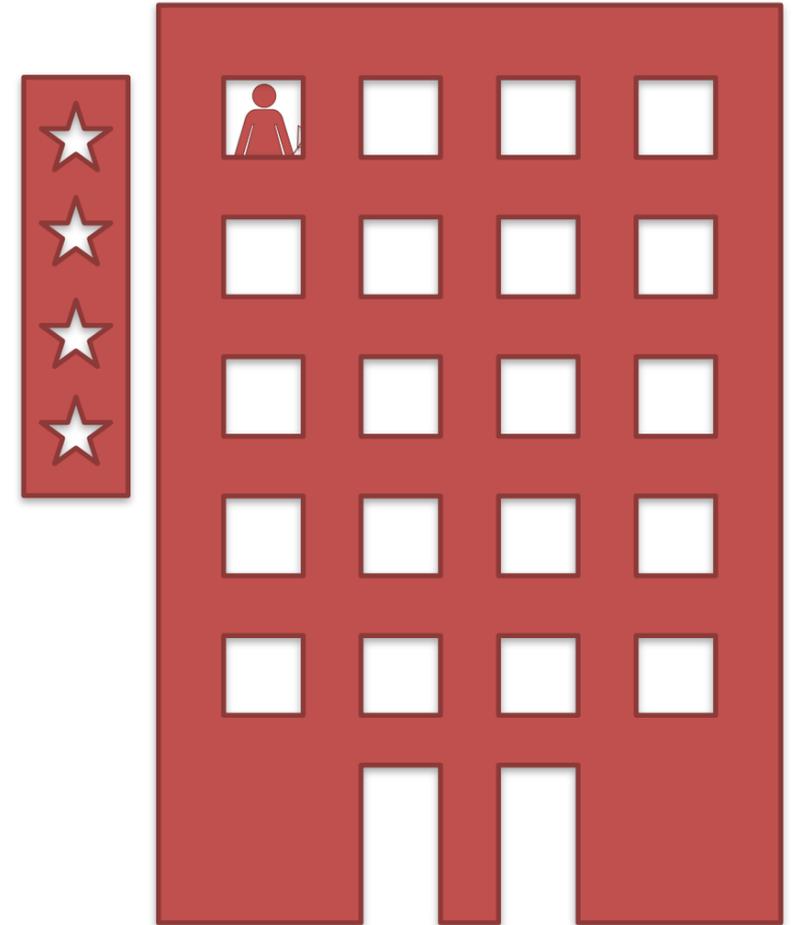
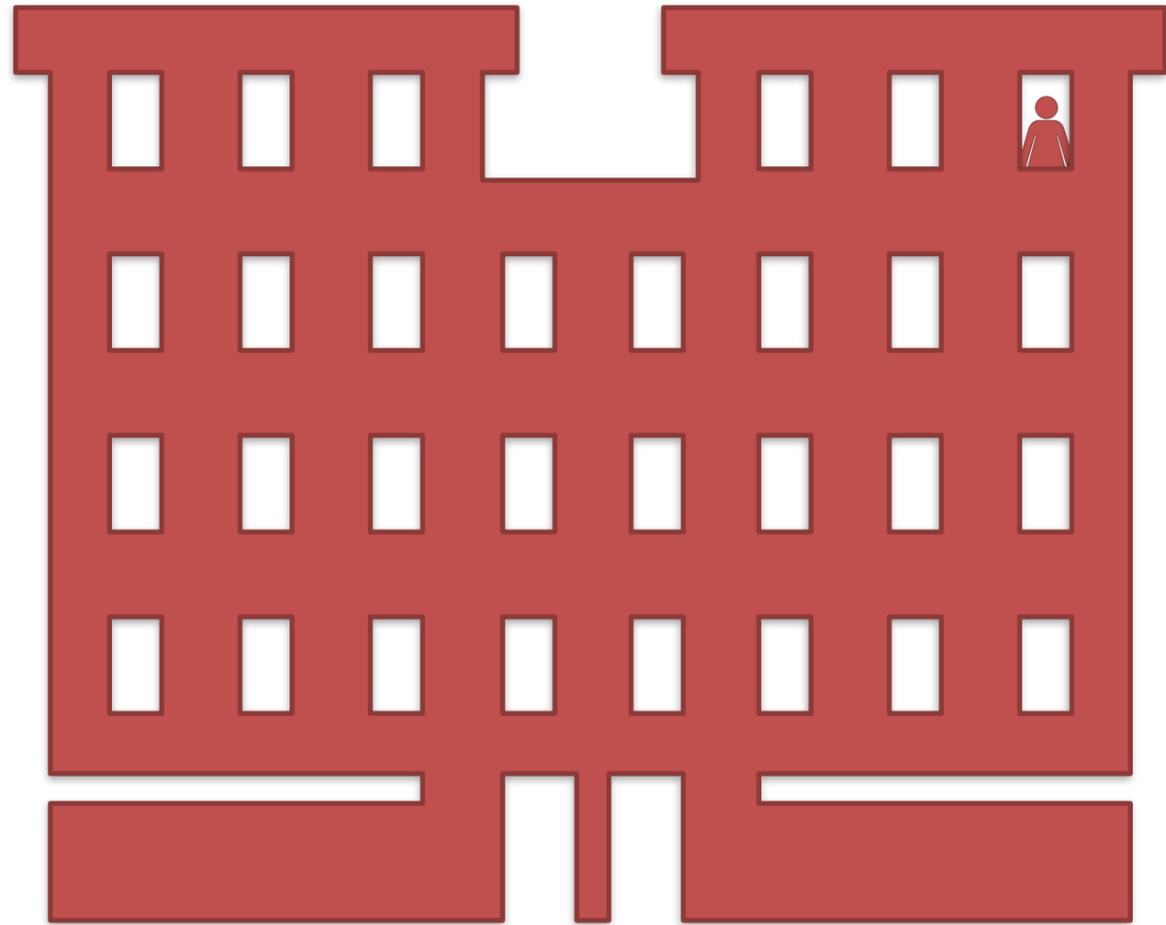
# Imagine...



# Imagine...

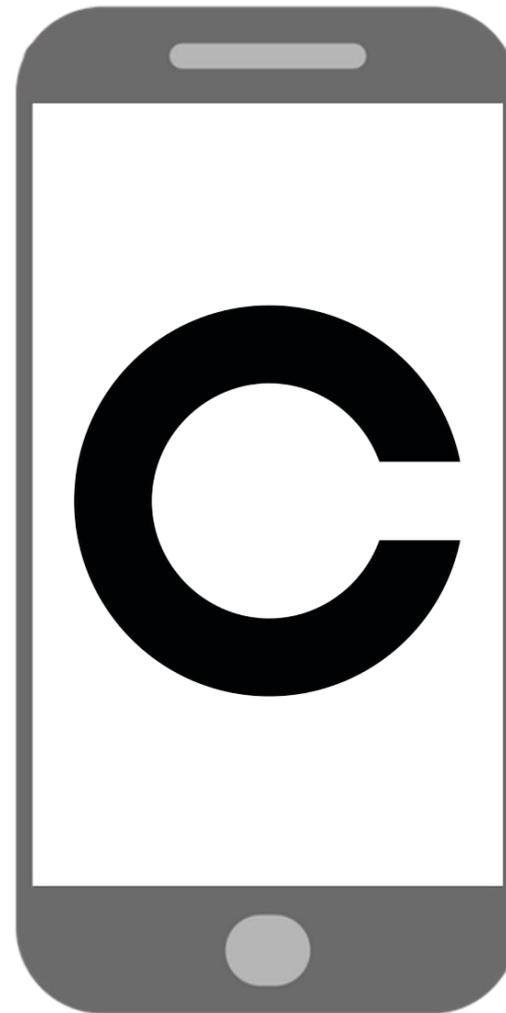


# Imagine...

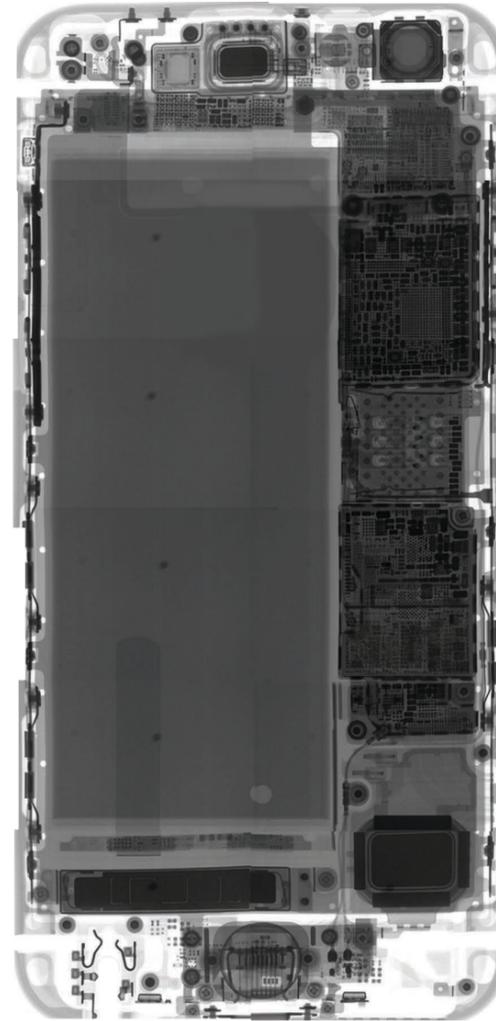


# The Setup

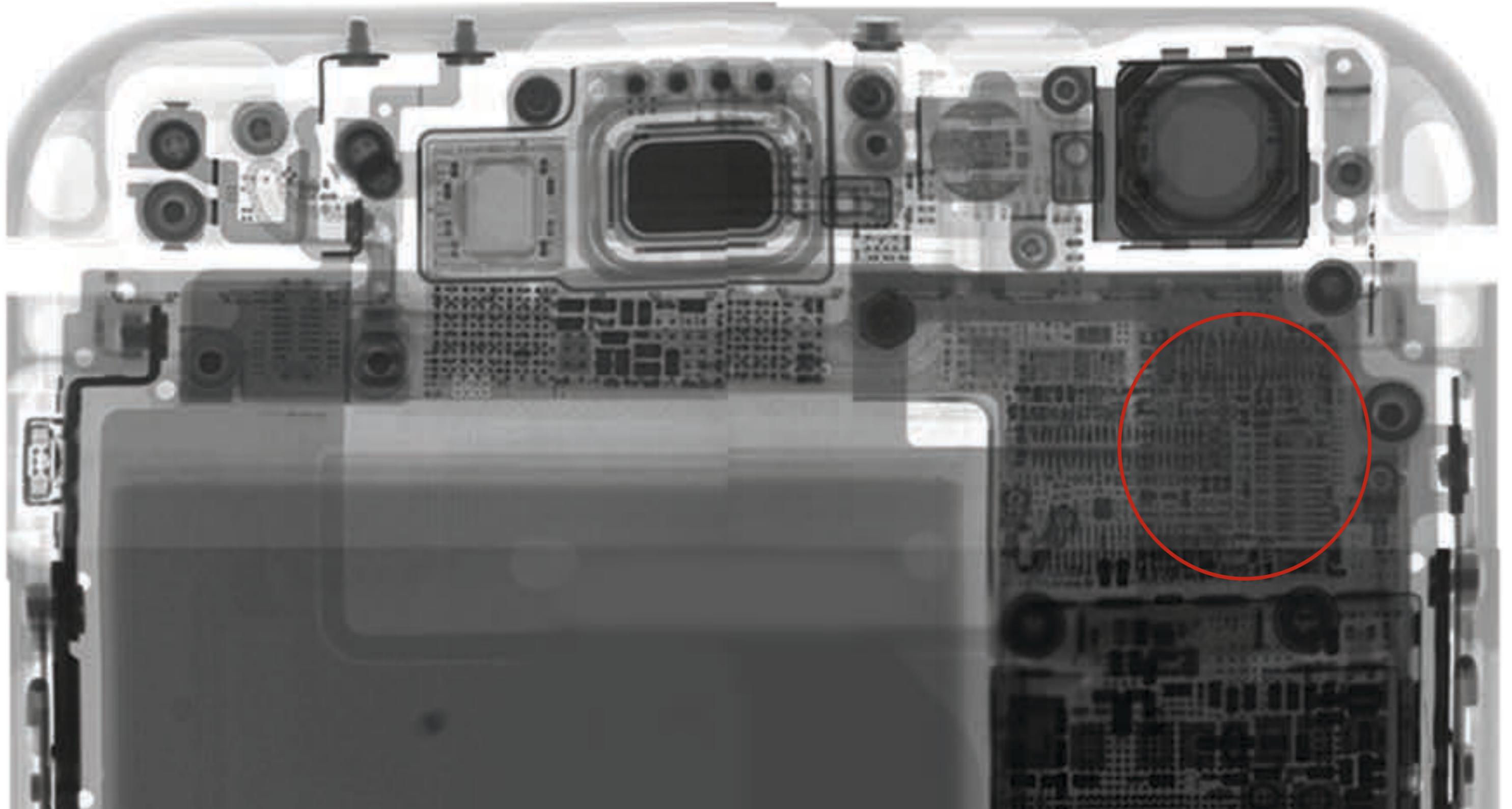
# The Setup



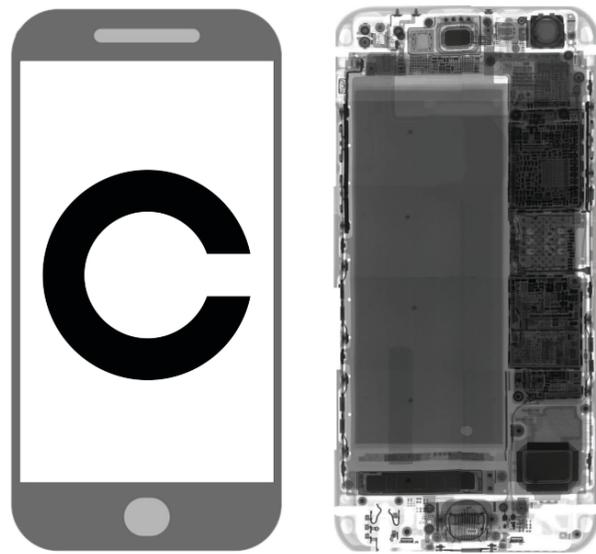
# The Setup



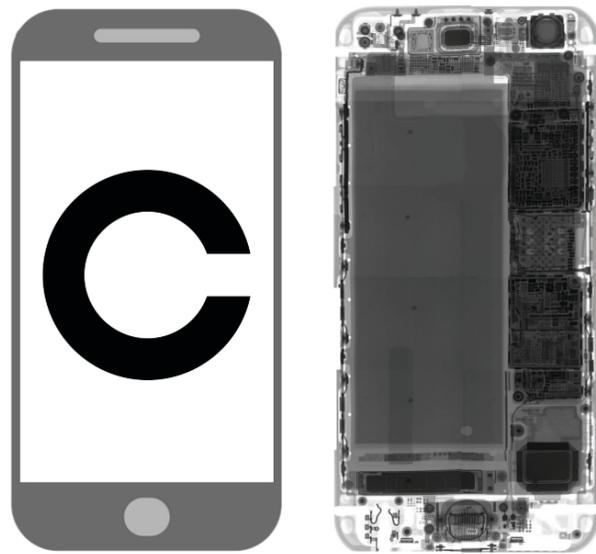
# The Setup



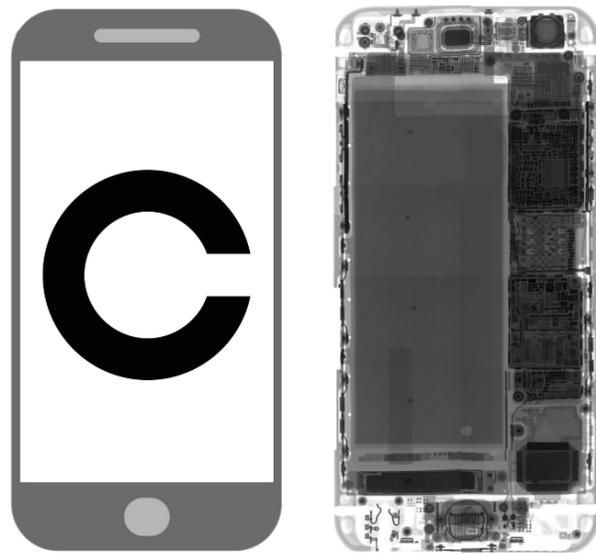
# The Setup



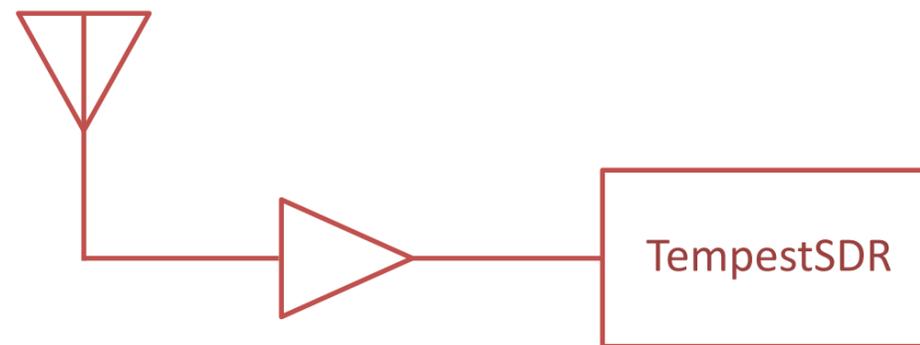
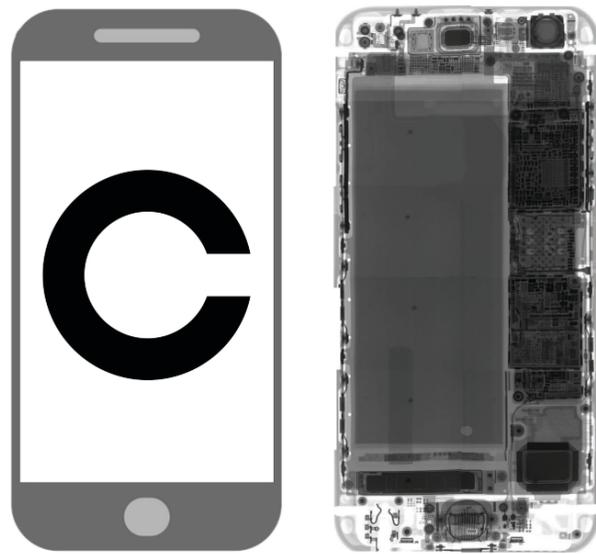
# The Setup



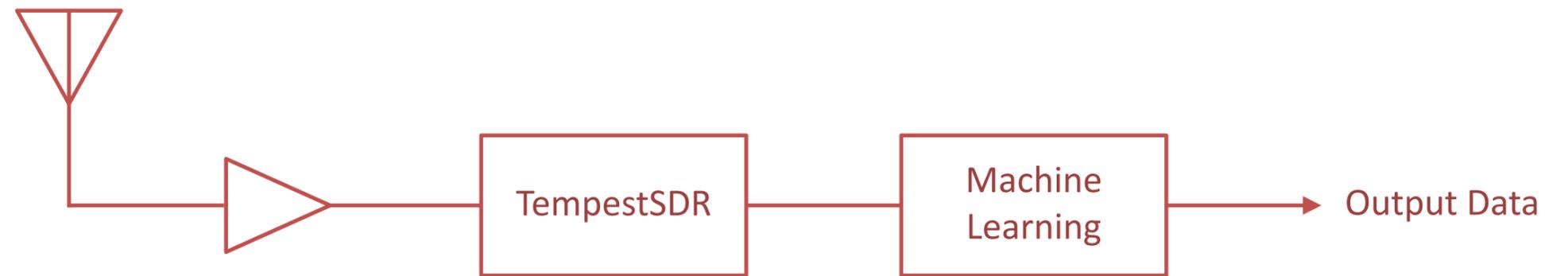
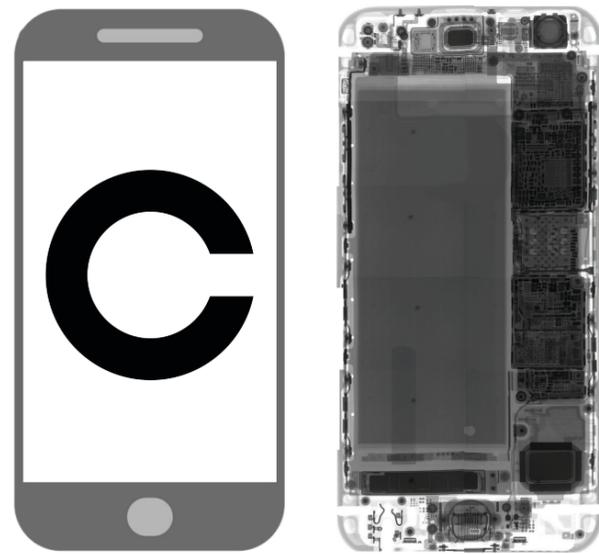
# The Setup



# The Setup

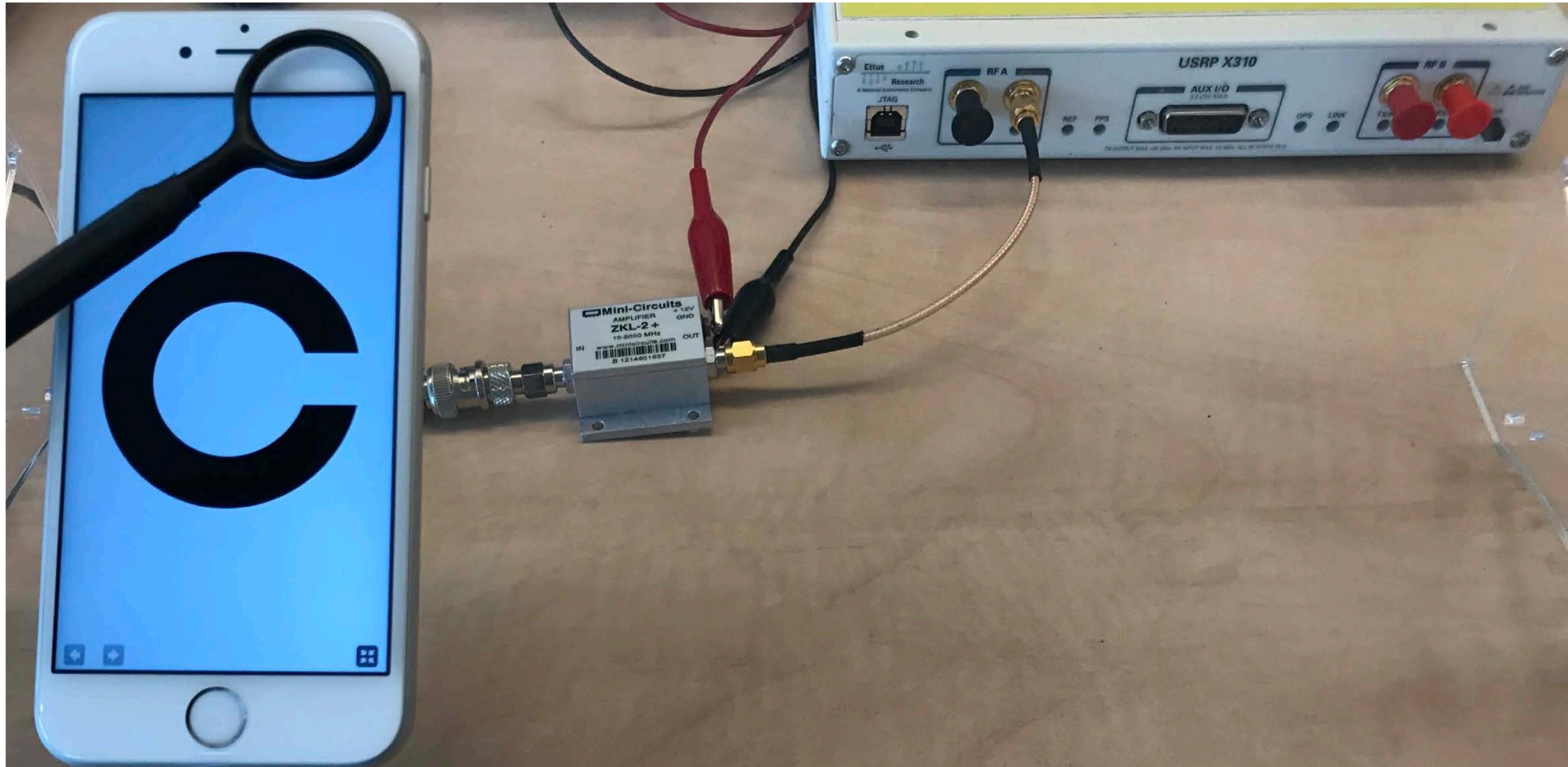


# The Setup

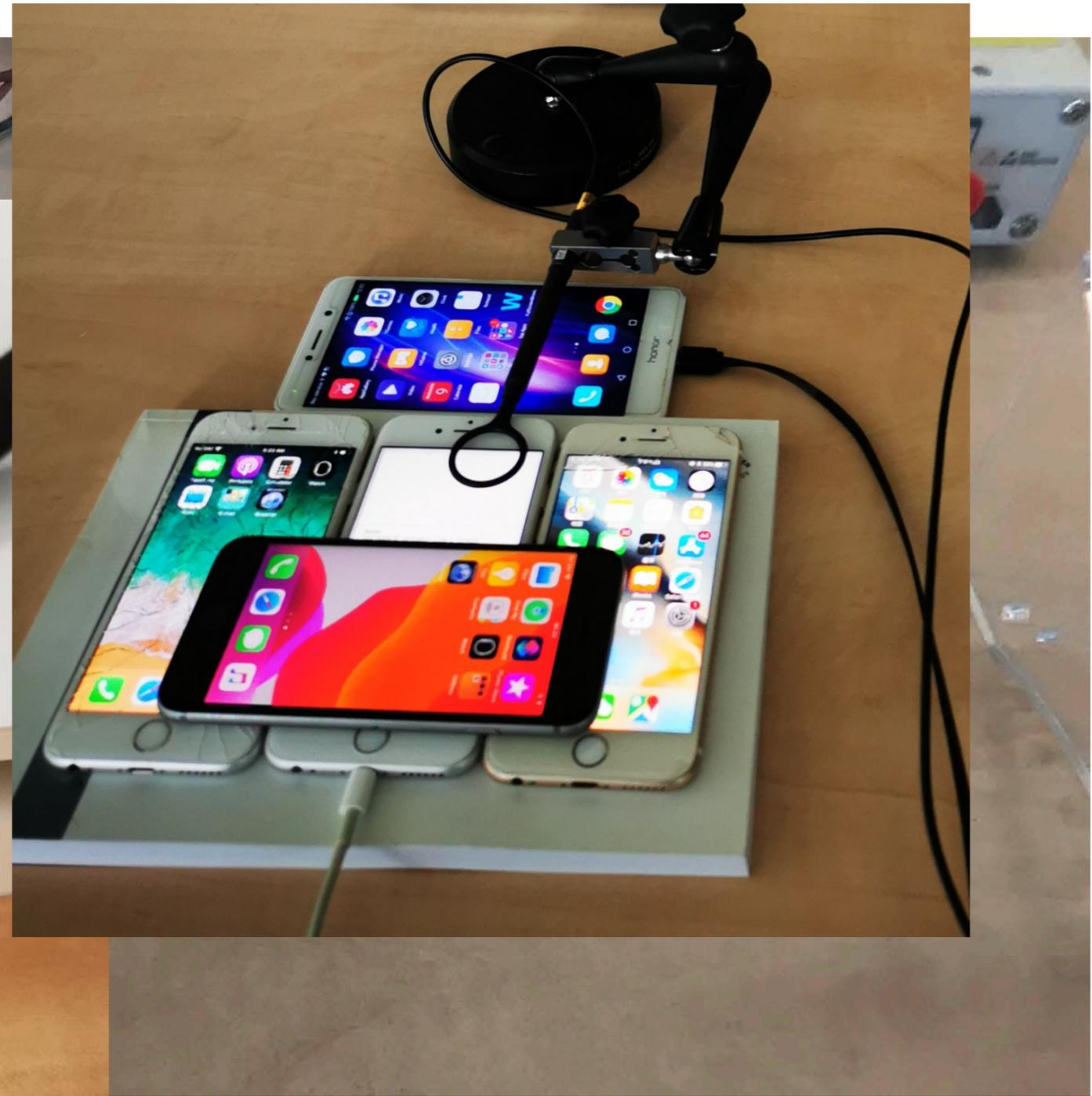


# Used Setup

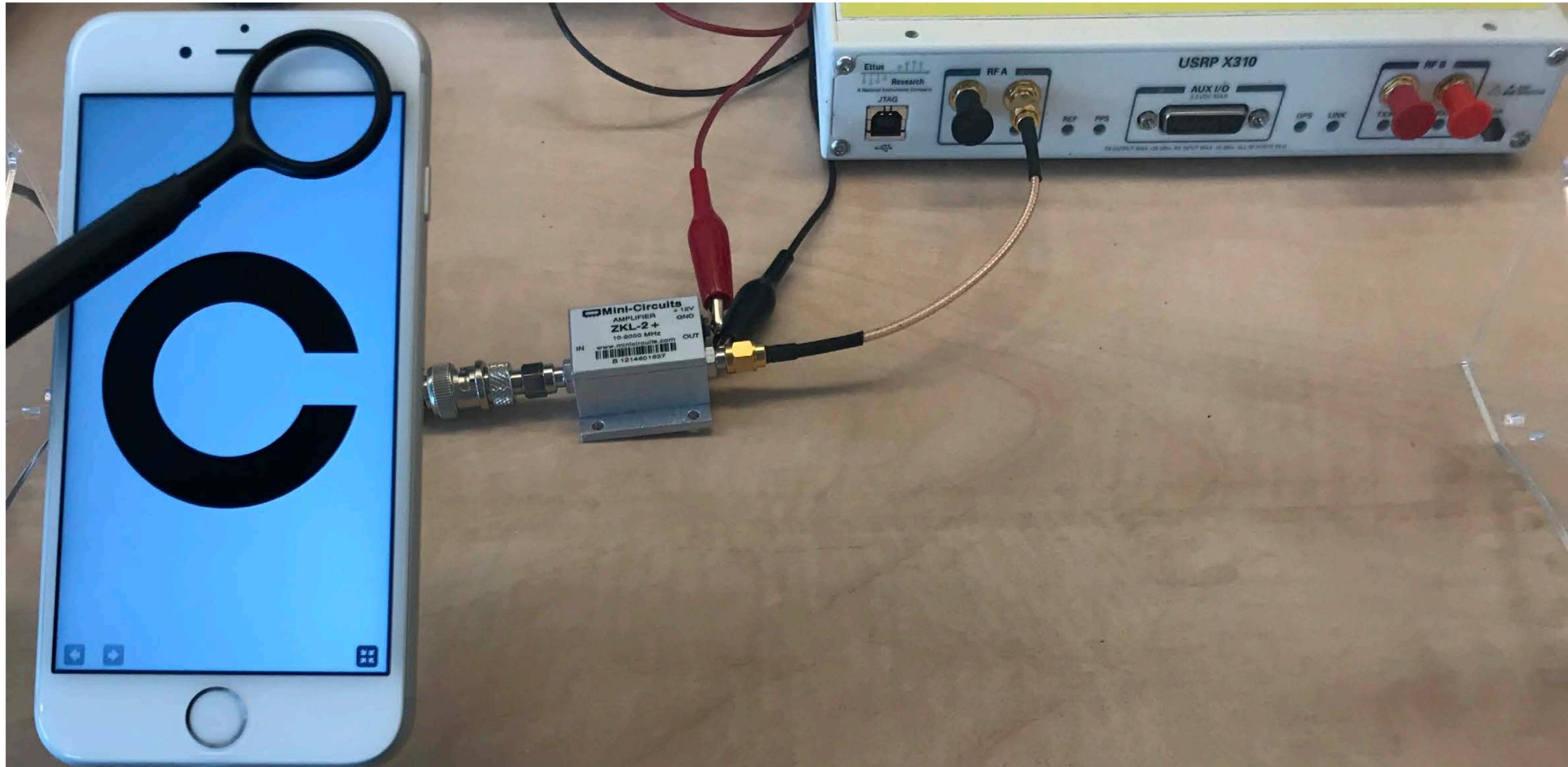
# Used Setup



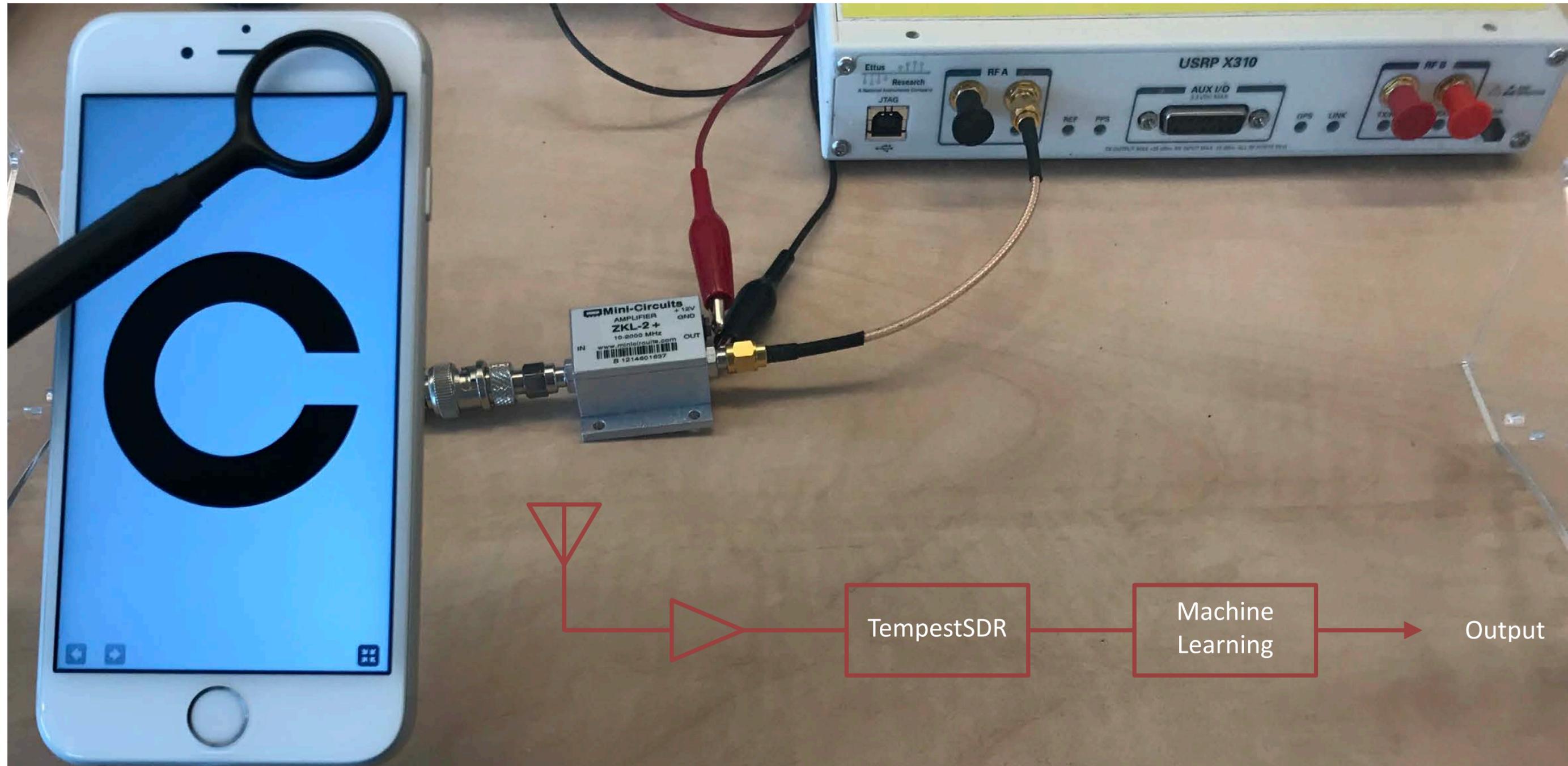
# Used Setup



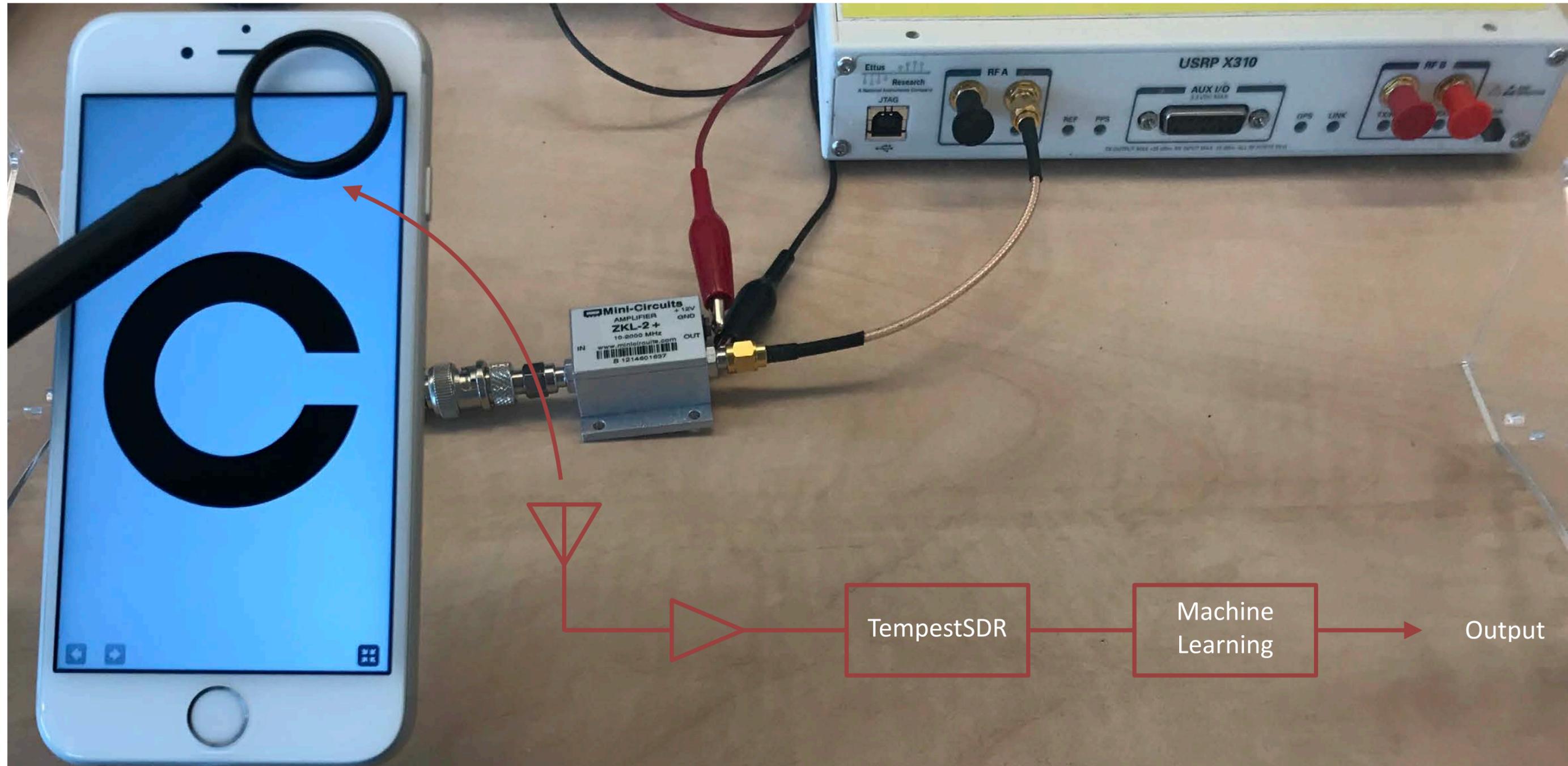
# Used Setup



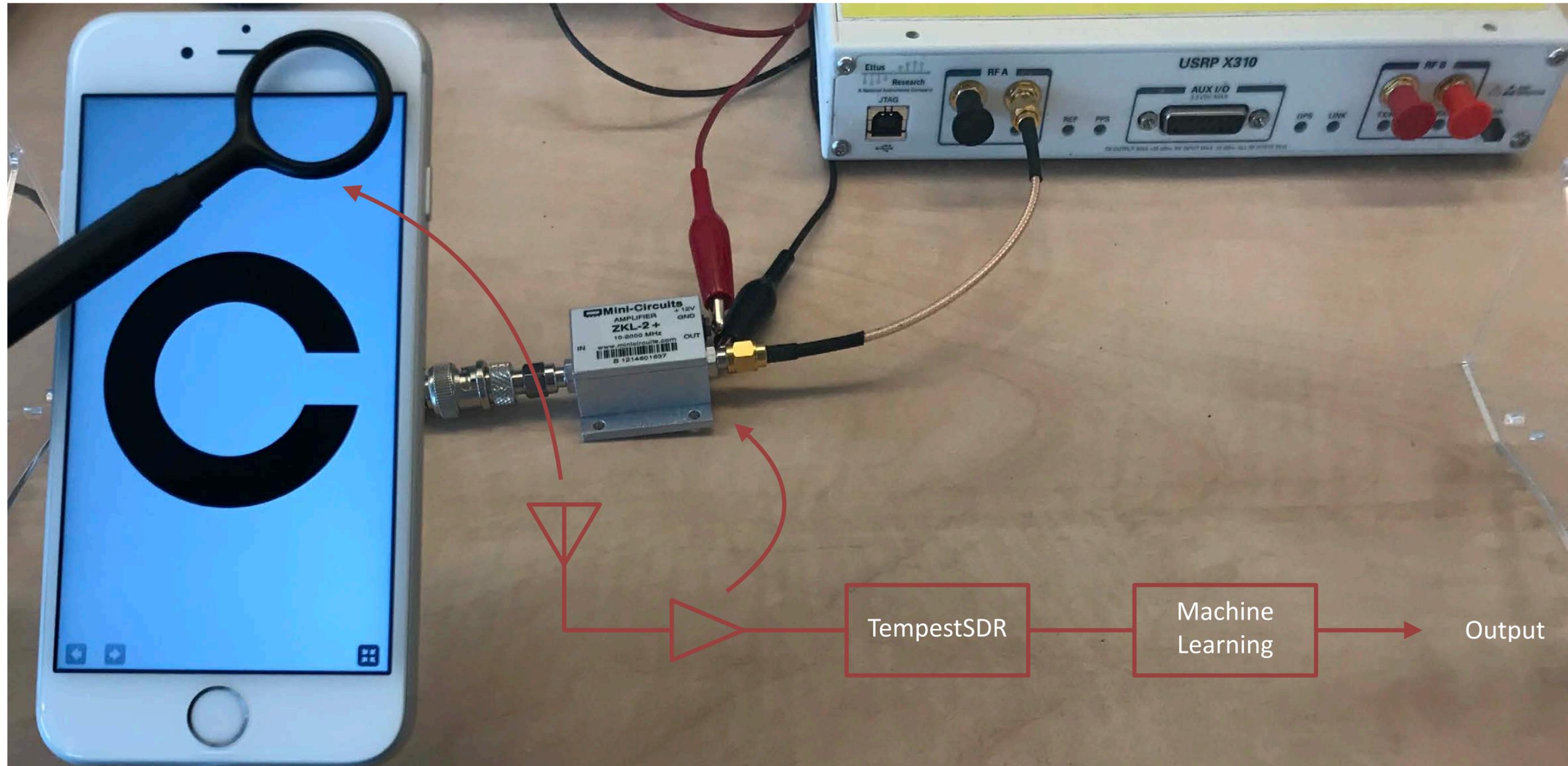
# Used Setup



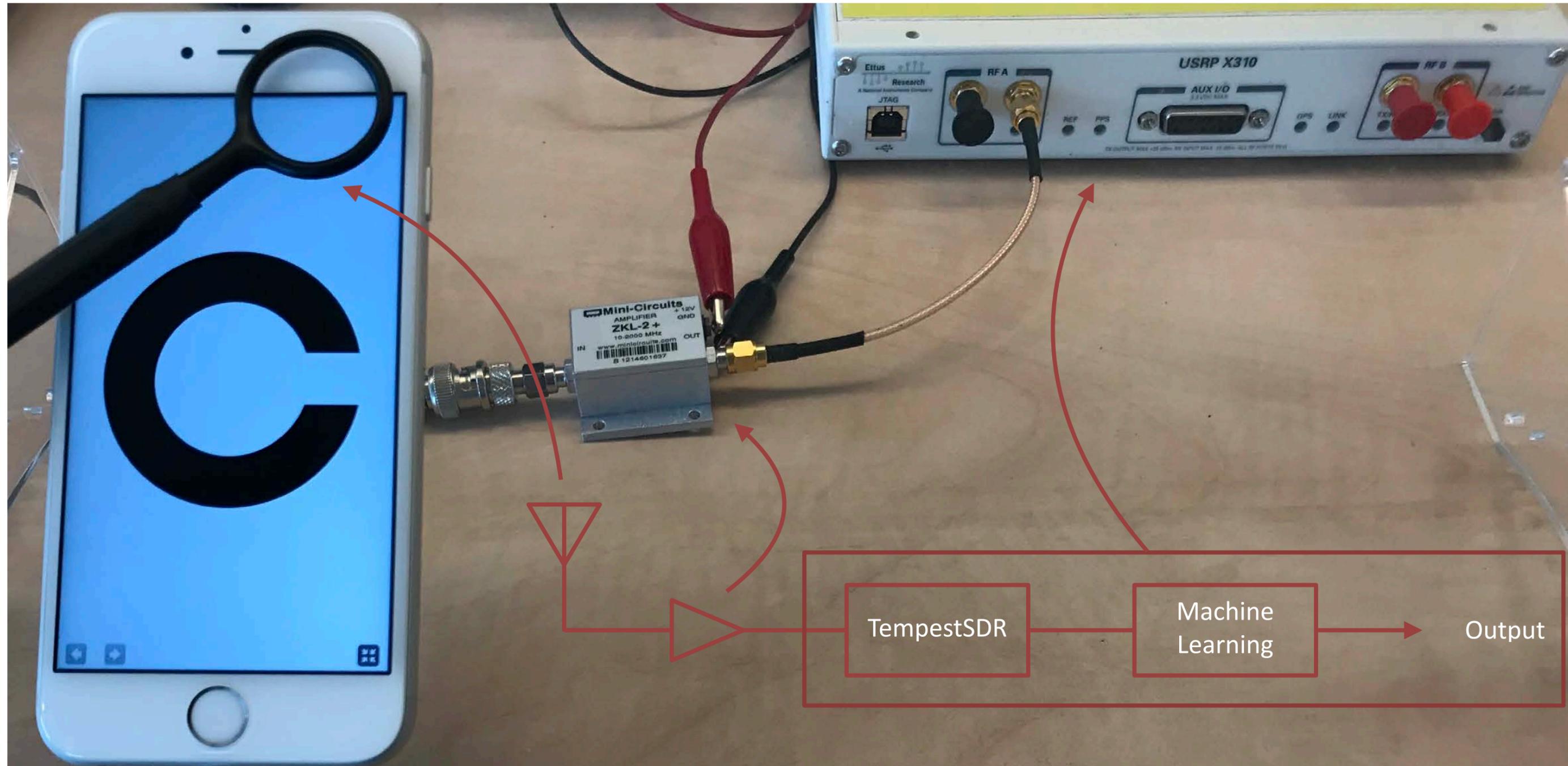
# Used Setup



# Used Setup



# Used Setup

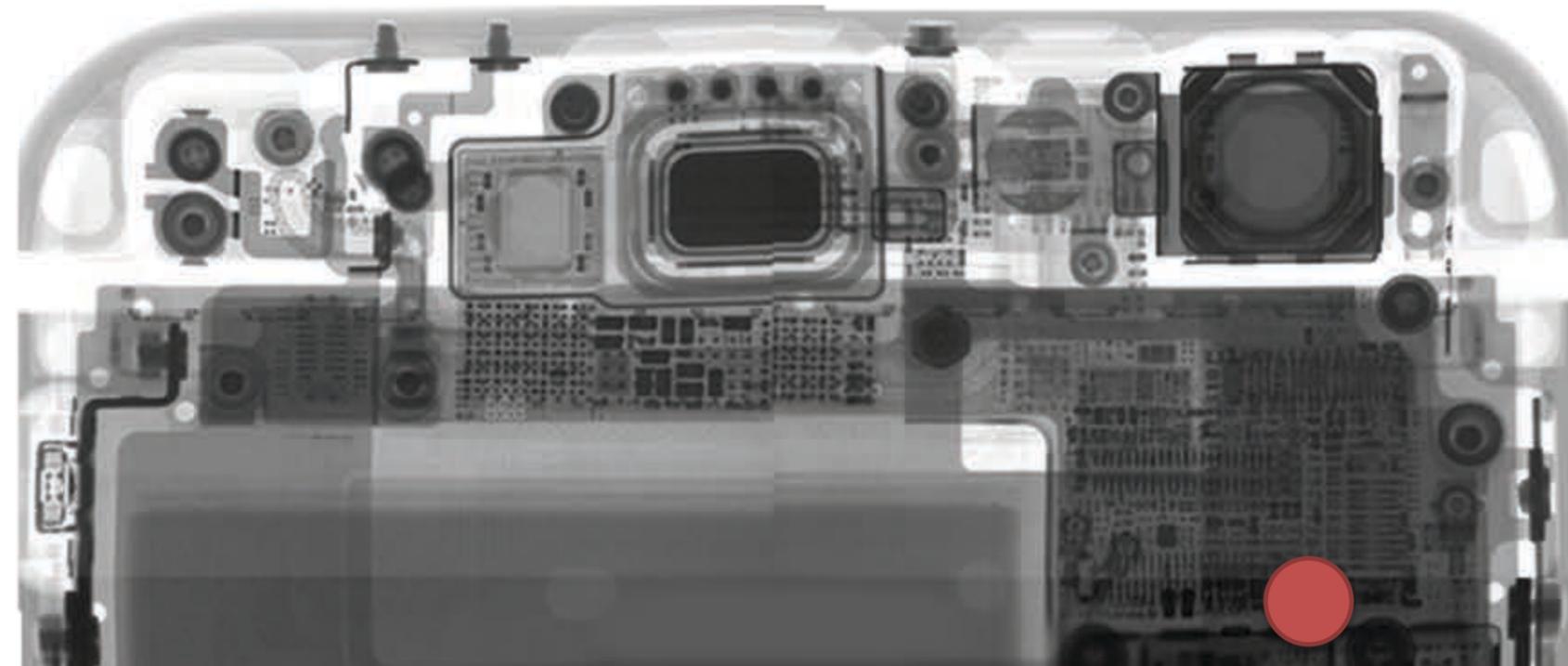


# Video Transmission

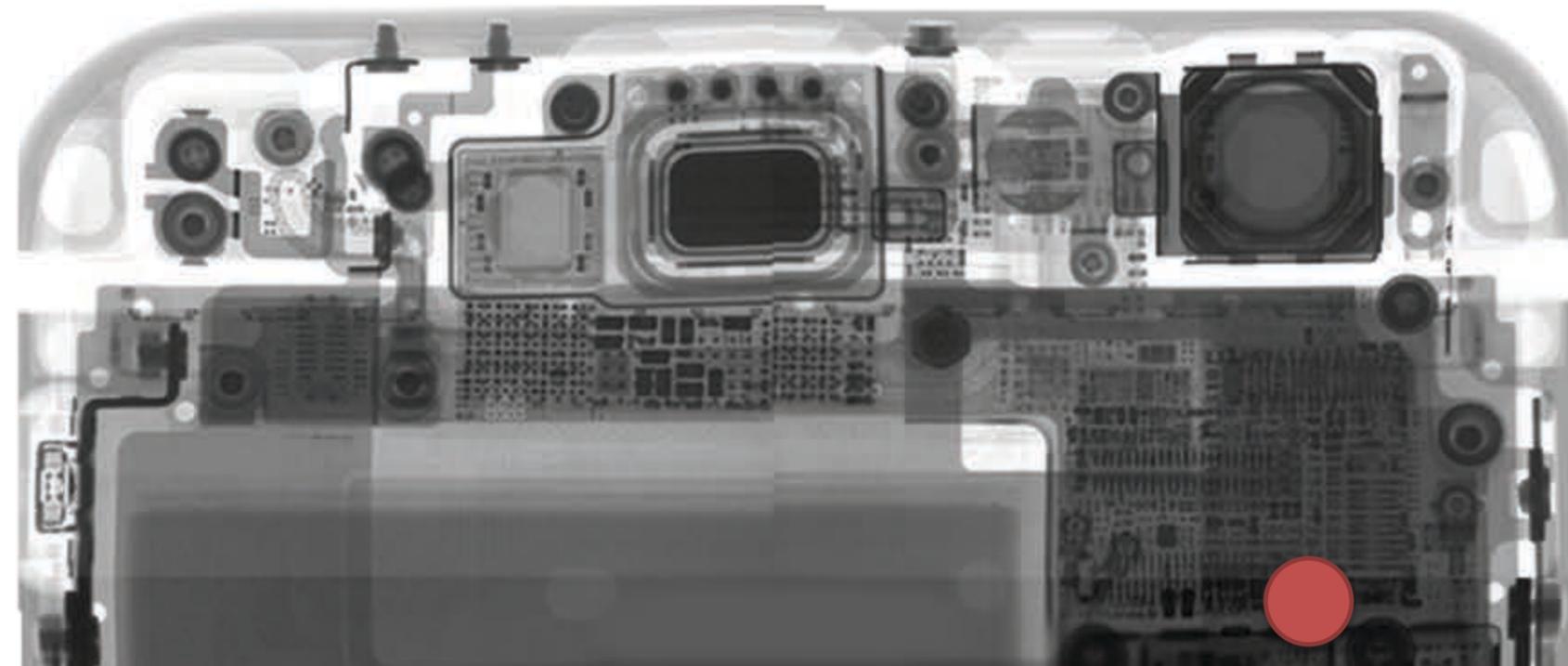
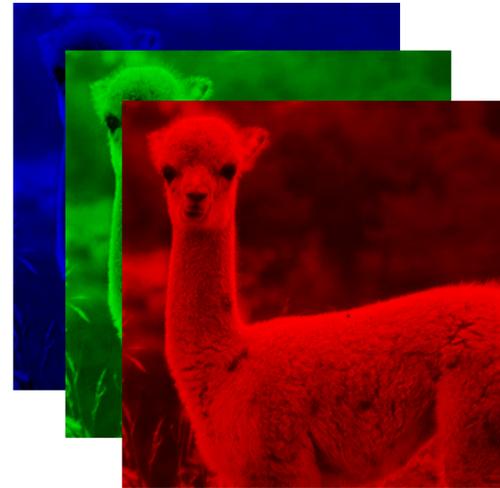
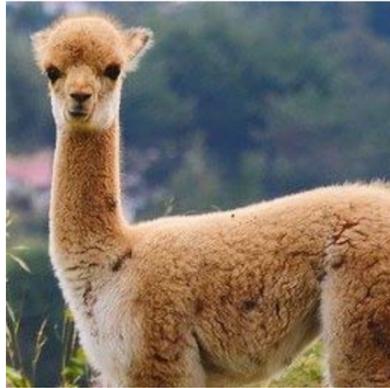
# Video Transmission



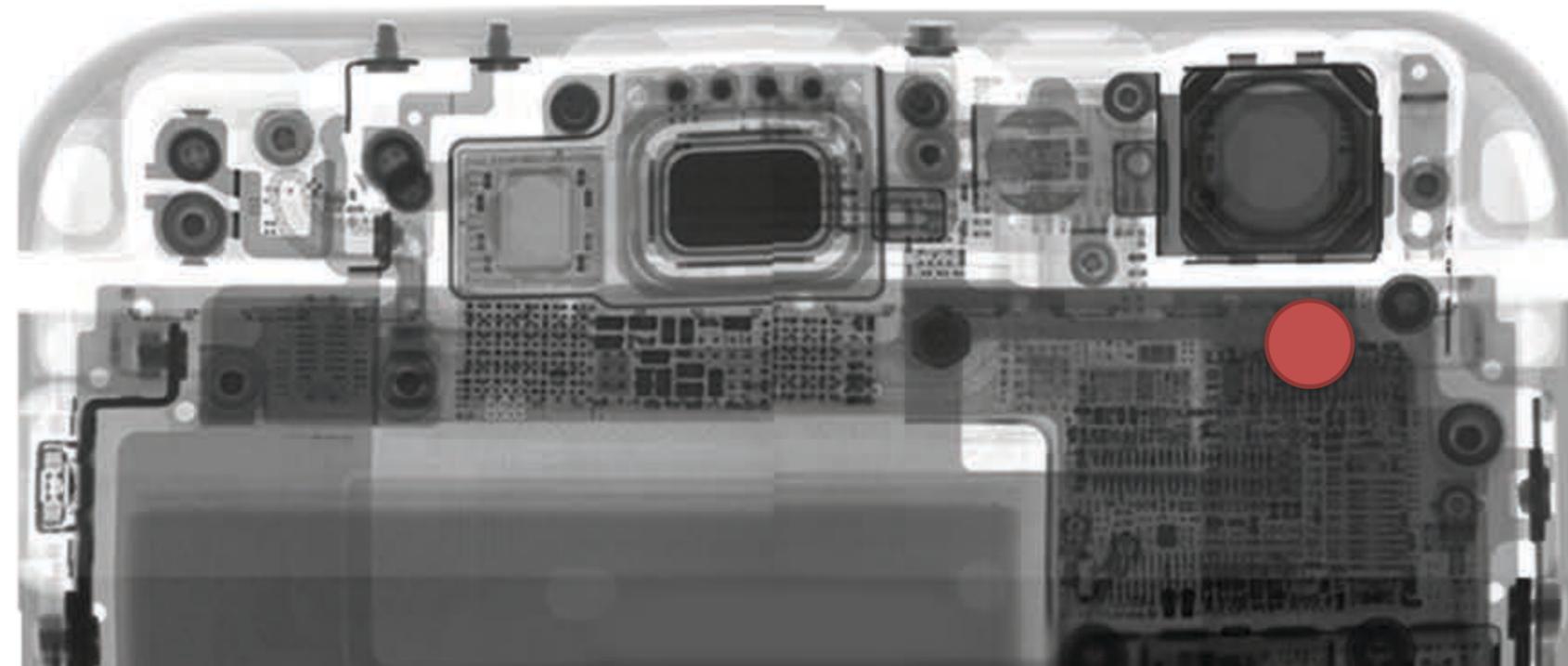
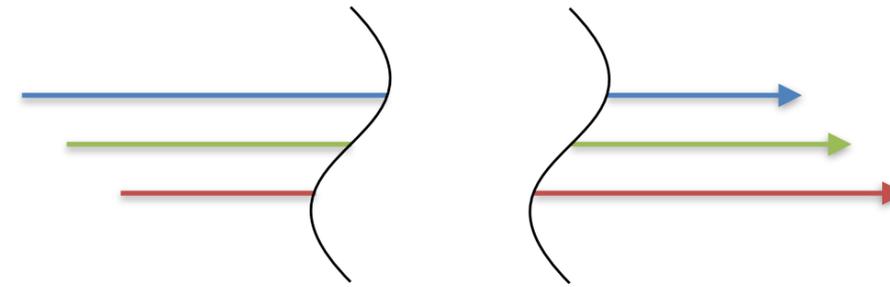
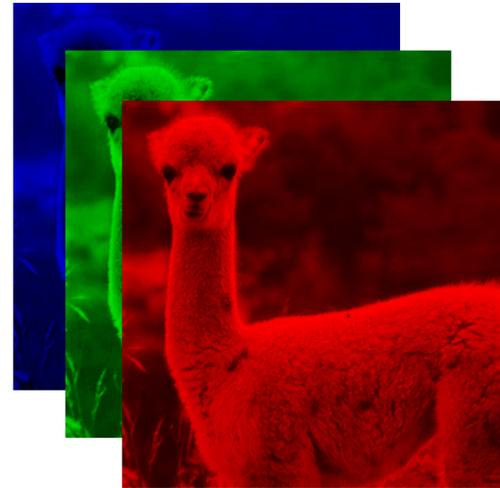
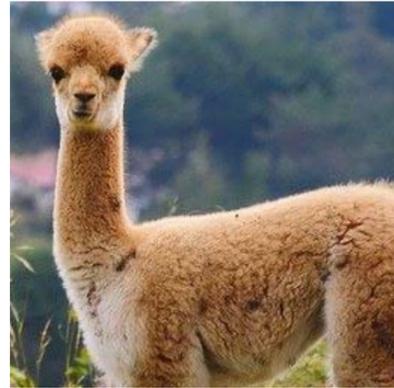
# Video Transmission



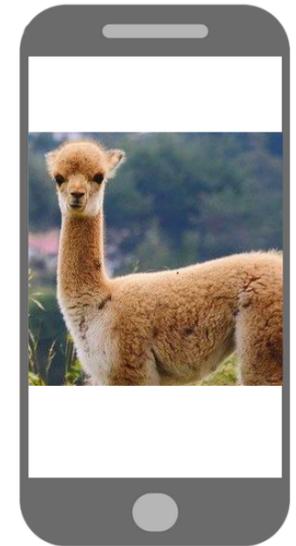
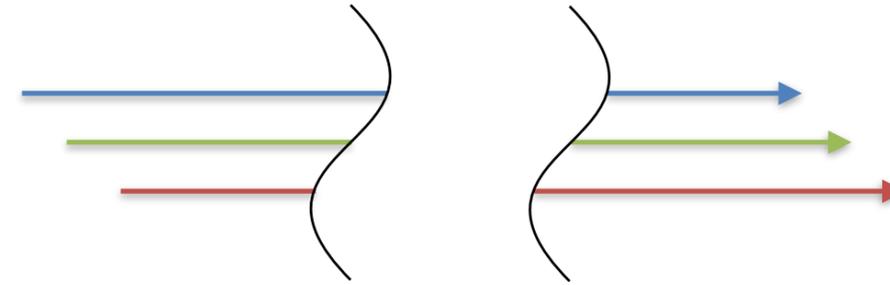
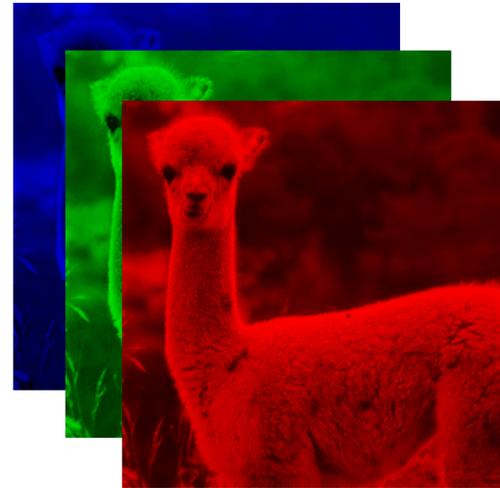
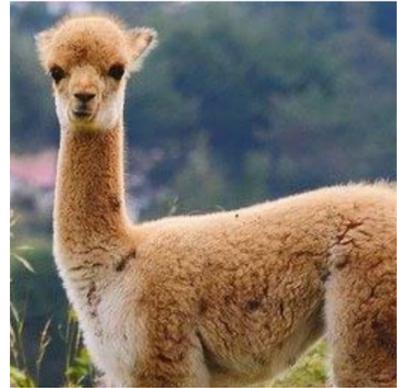
# Video Transmission



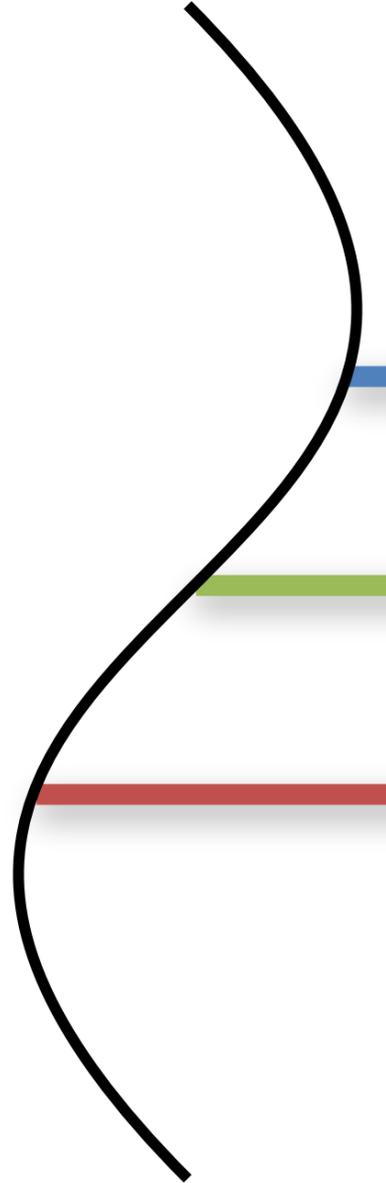
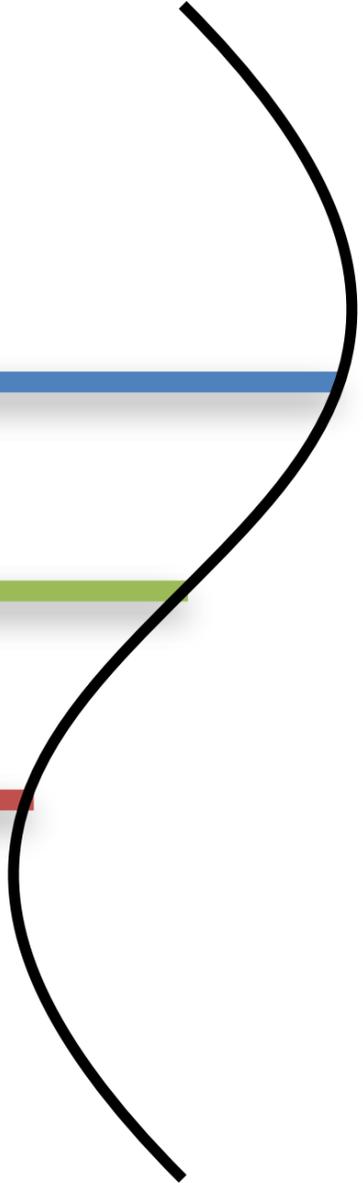
# Video Transmission



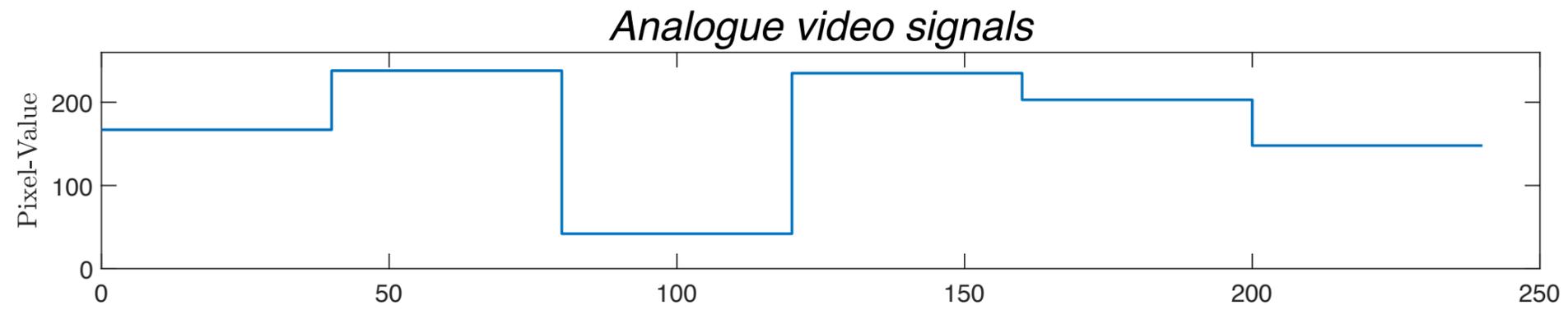
# Video Transmission



# Video Transmission

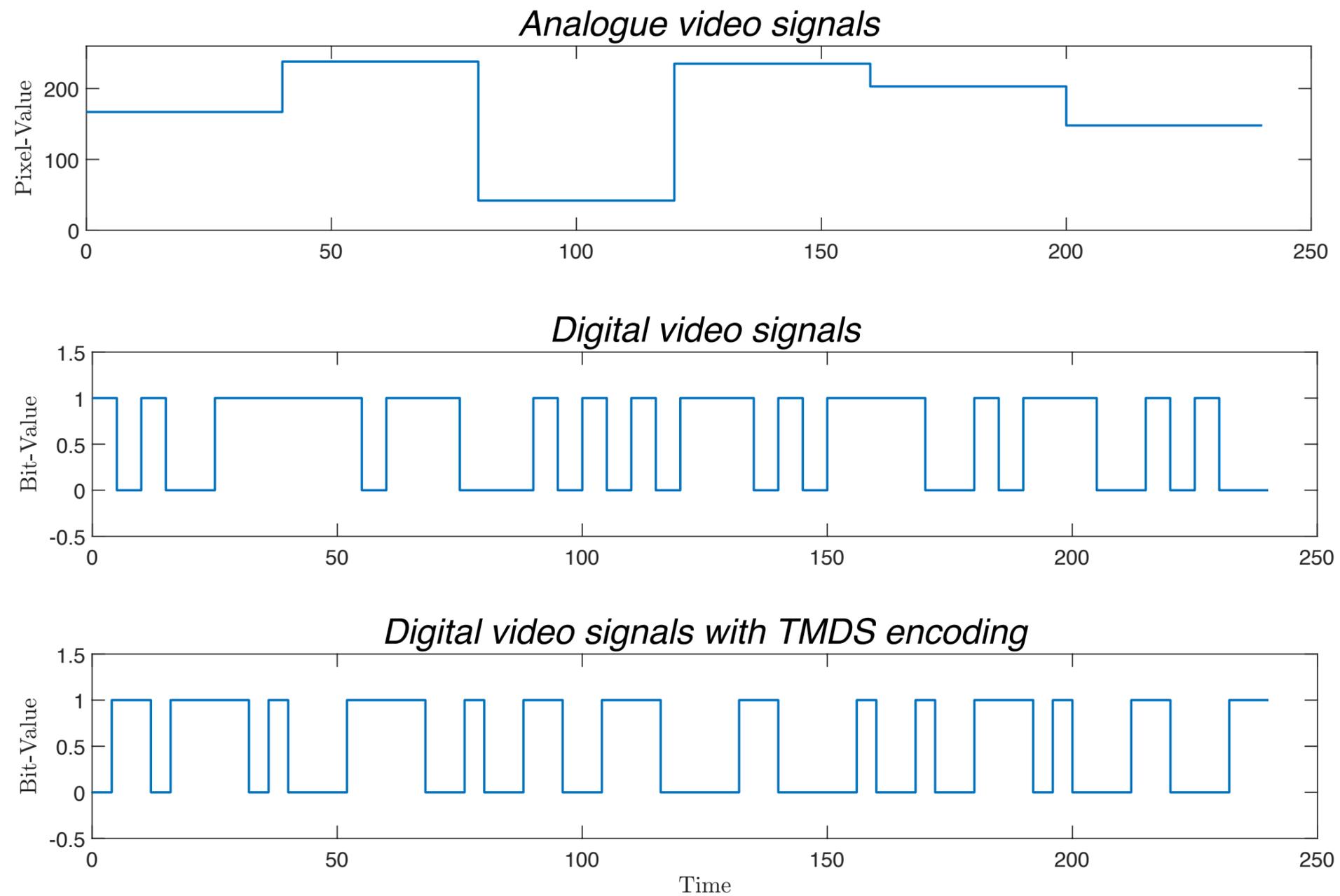


# Video Transmission



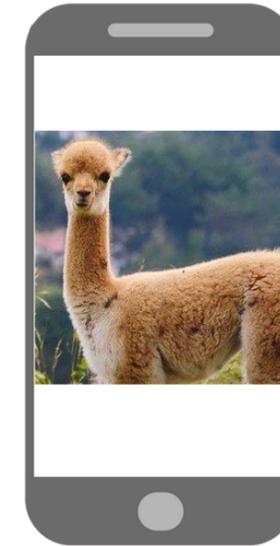
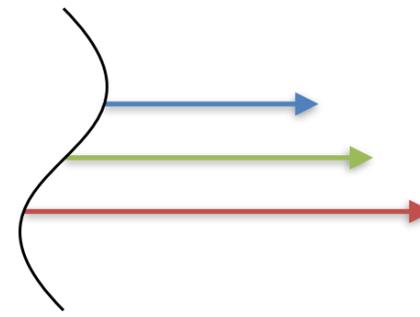
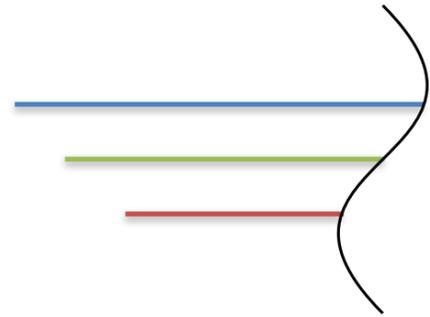


# Video Transmission

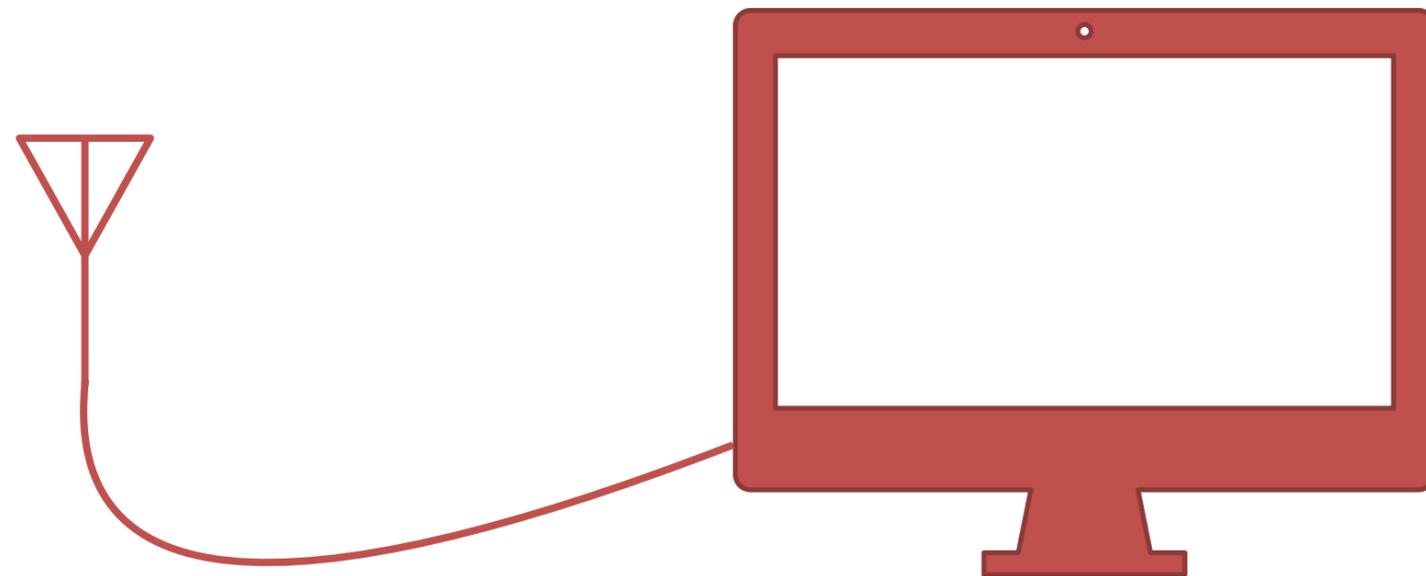
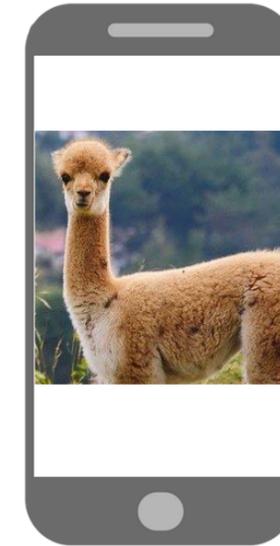
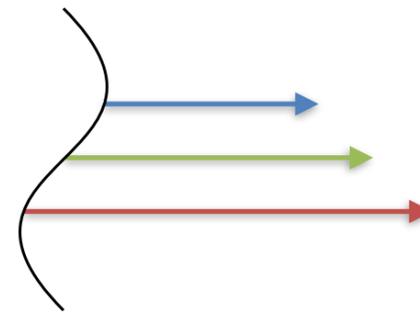
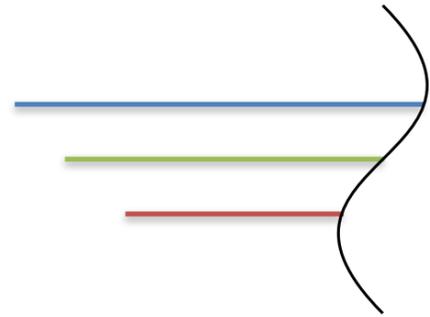


# Electromagnetic Emanations

# Electromagnetic Emanations

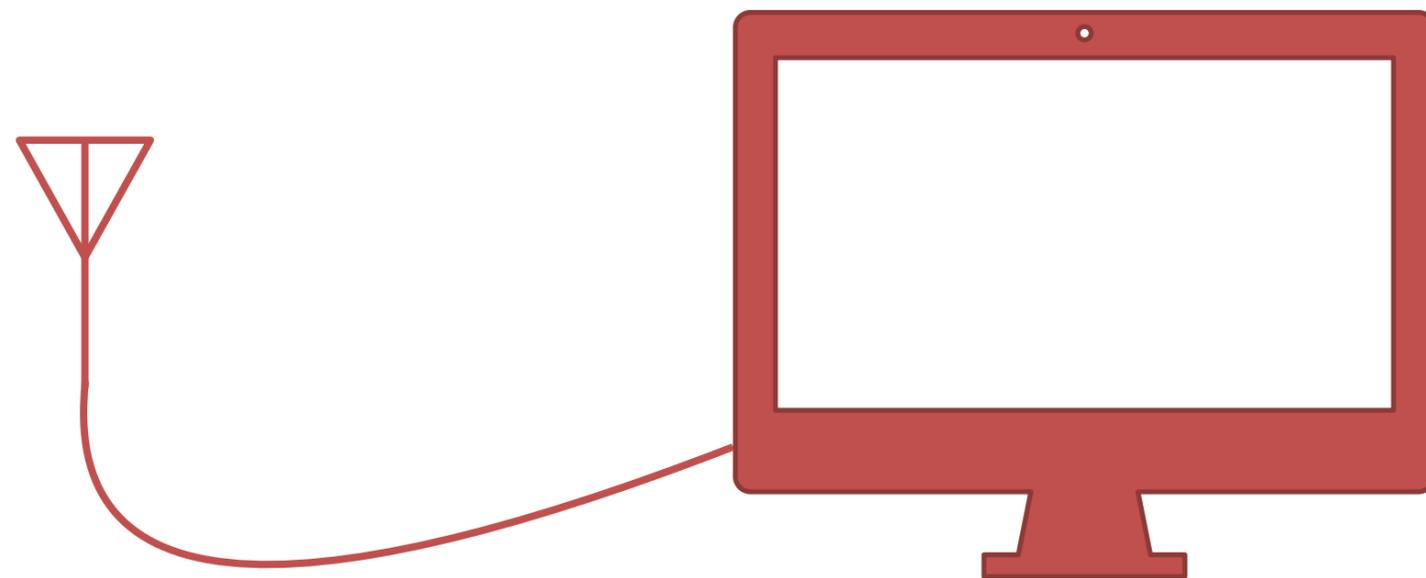
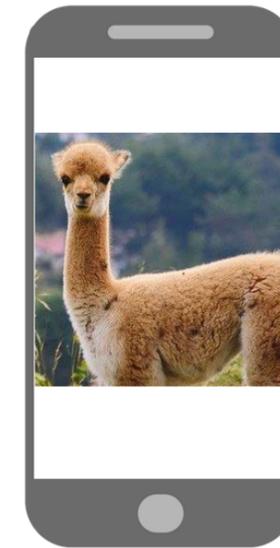
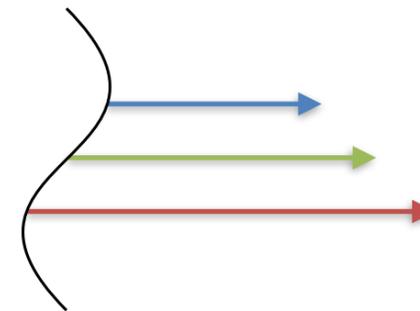
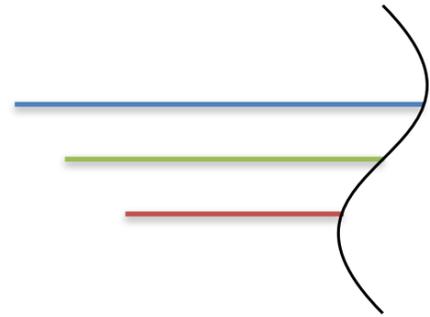


# Electromagnetic Emanations



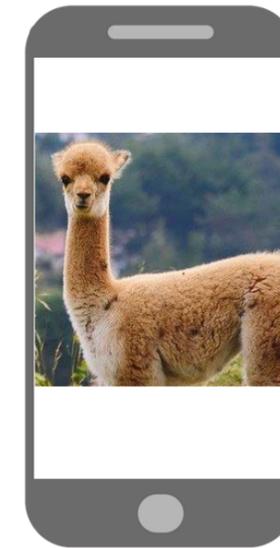
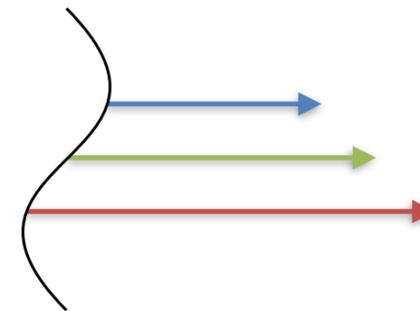
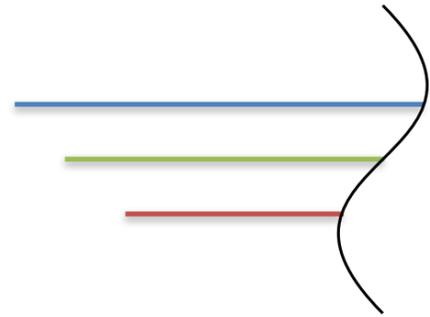
# Electromagnetic Emanations

Digital or analogue transmission



# Electromagnetic Emanations

Digital or analogue transmission



# CONTENTS

# Table of Contents

# Table of Contents

1. Antenna Design

# Table of Contents

1. Antenna Design
2. TempestSDR

# Table of Contents

1. Antenna Design
2. TempestSDR
3. Machine Learning

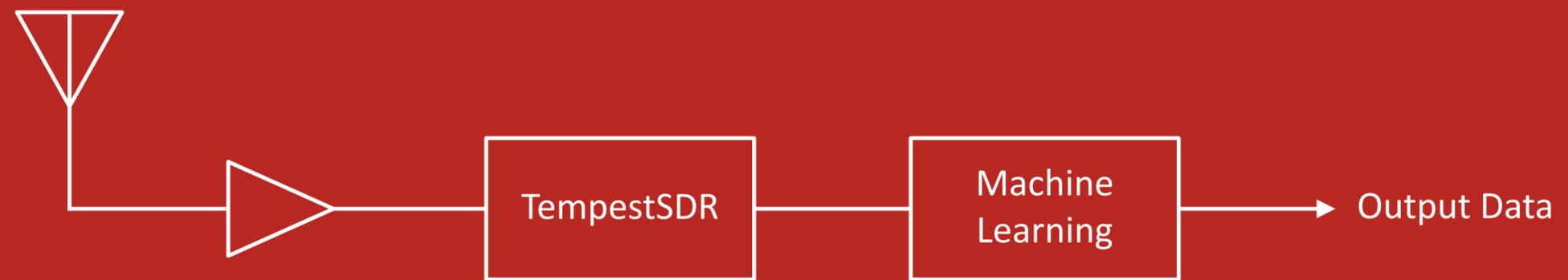
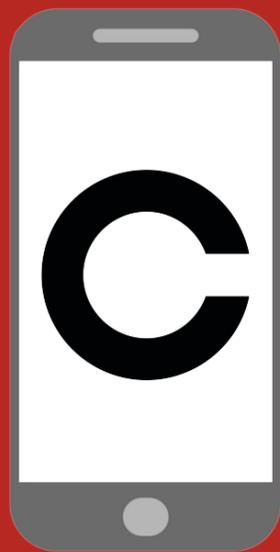
# Table of Contents

1. Antenna Design
2. TempestSDR
3. Machine Learning
4. Outlook

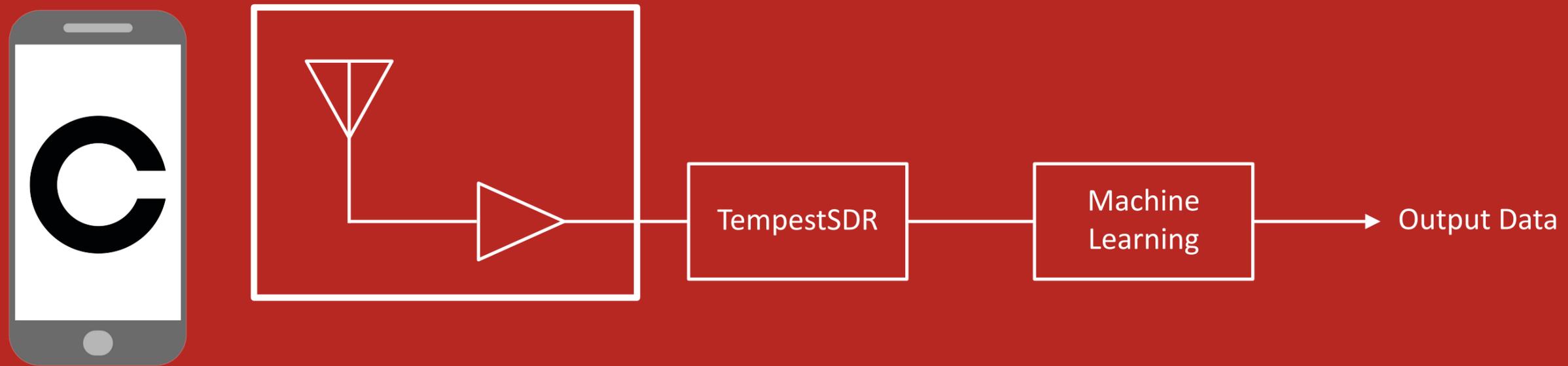
# Table of Contents

1. Antenna Design
2. TempestSDR
3. Machine Learning
4. Outlook
5. Discussion

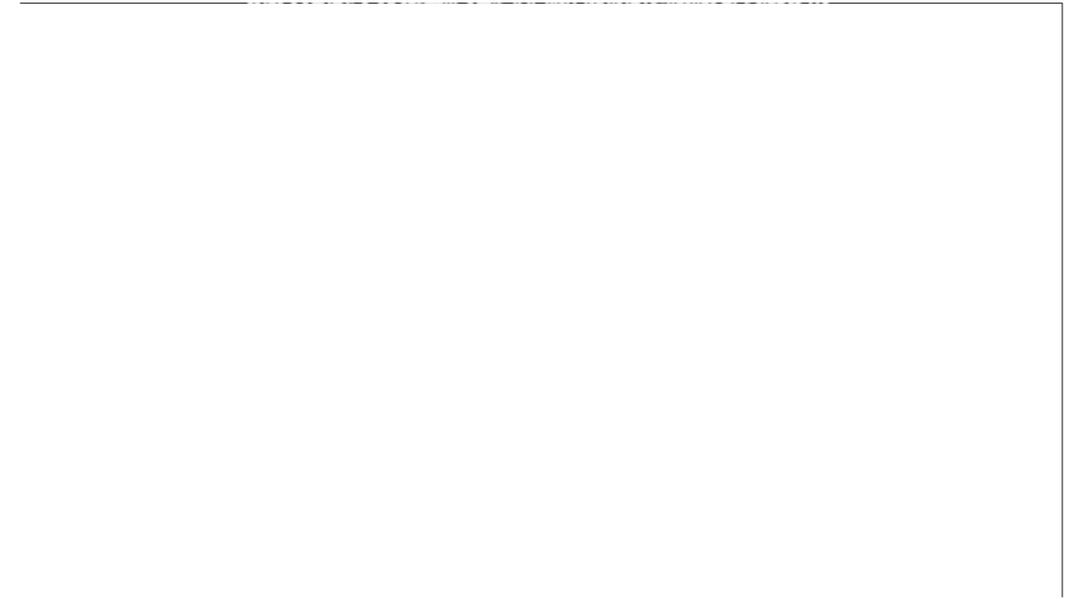
# Antenna Design



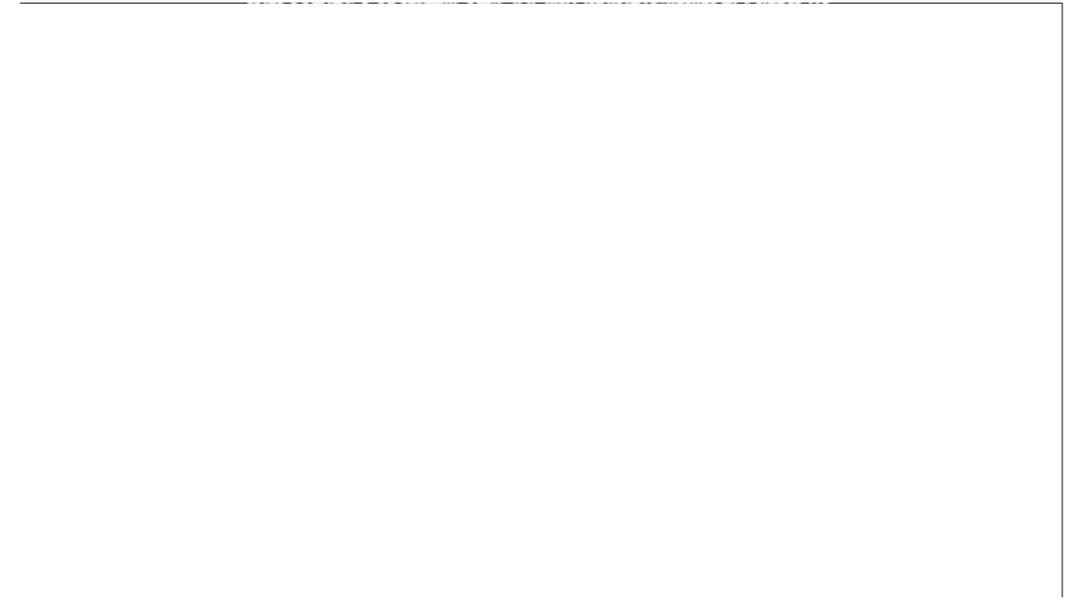
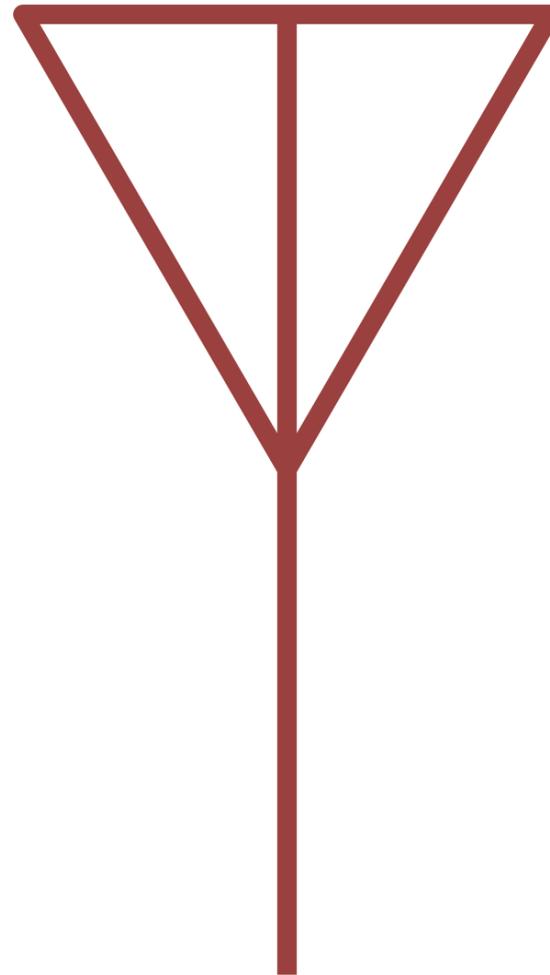
# Antenna Design



# Antenna Positioning

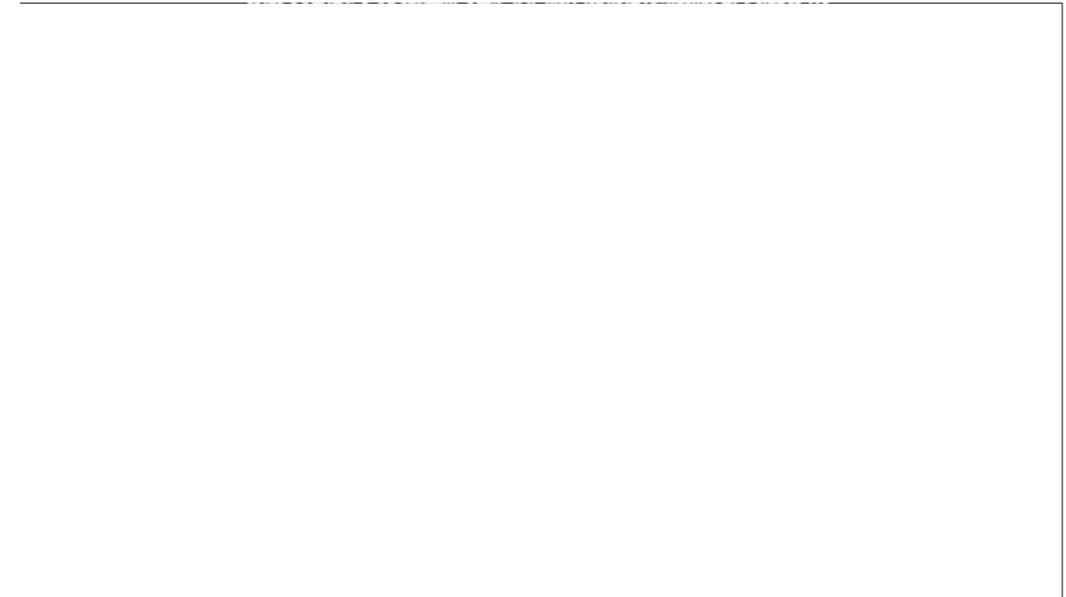
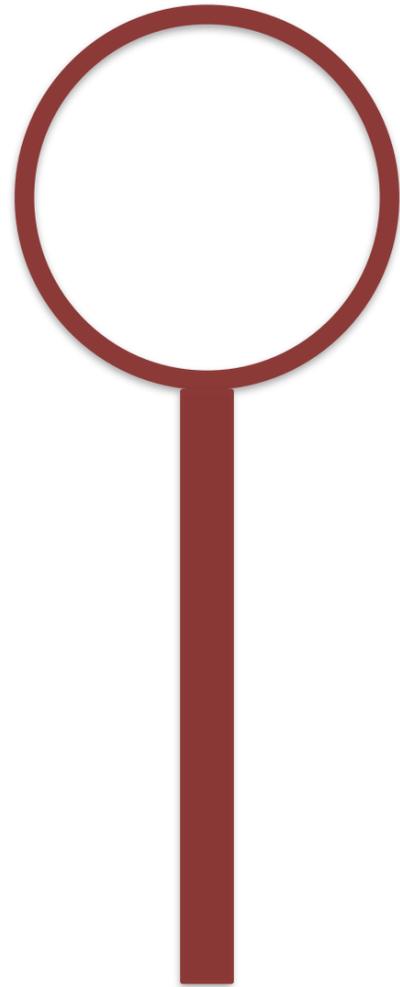


# Antenna Positioning



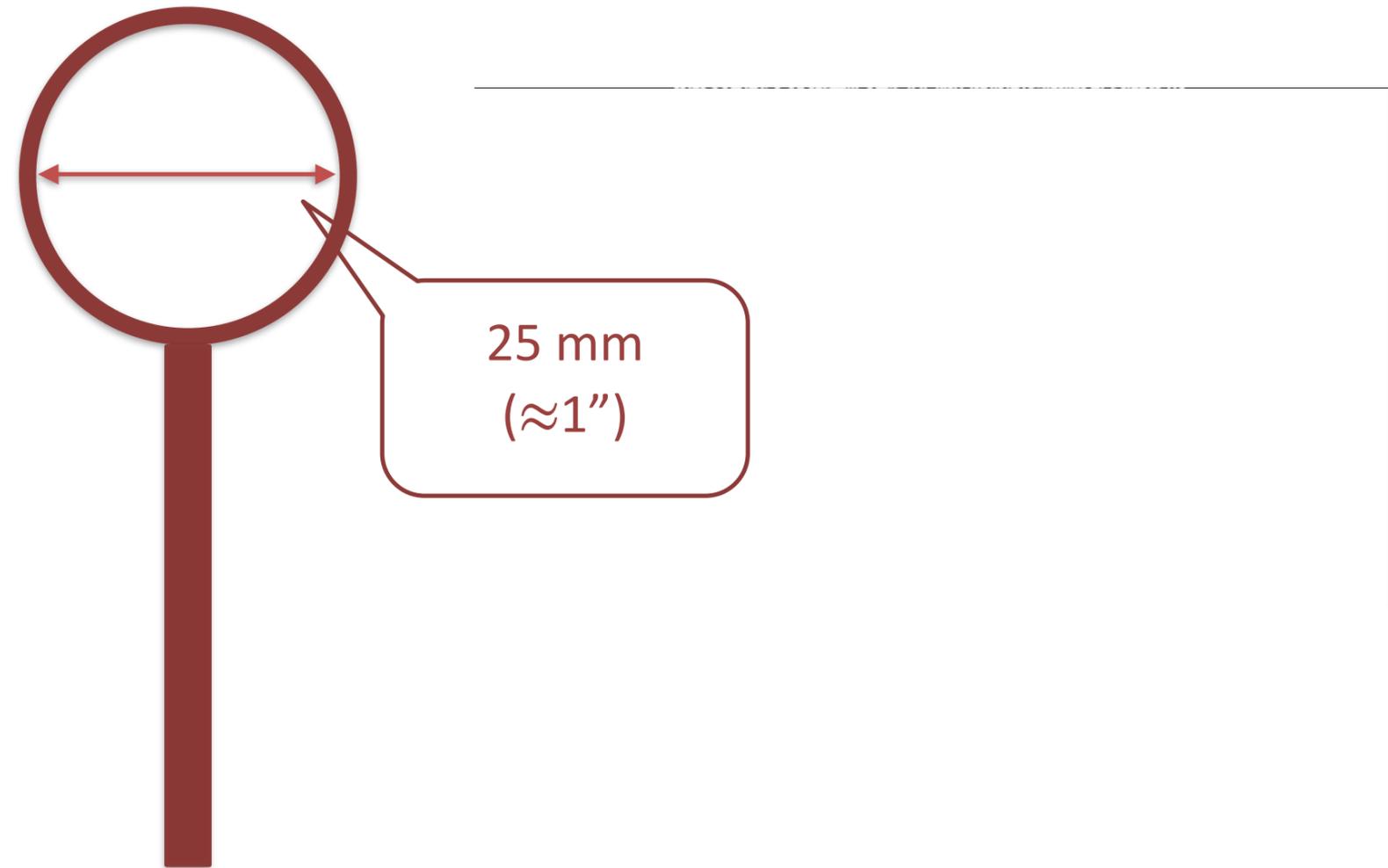
# Antenna Positioning

Langer RF-R 400



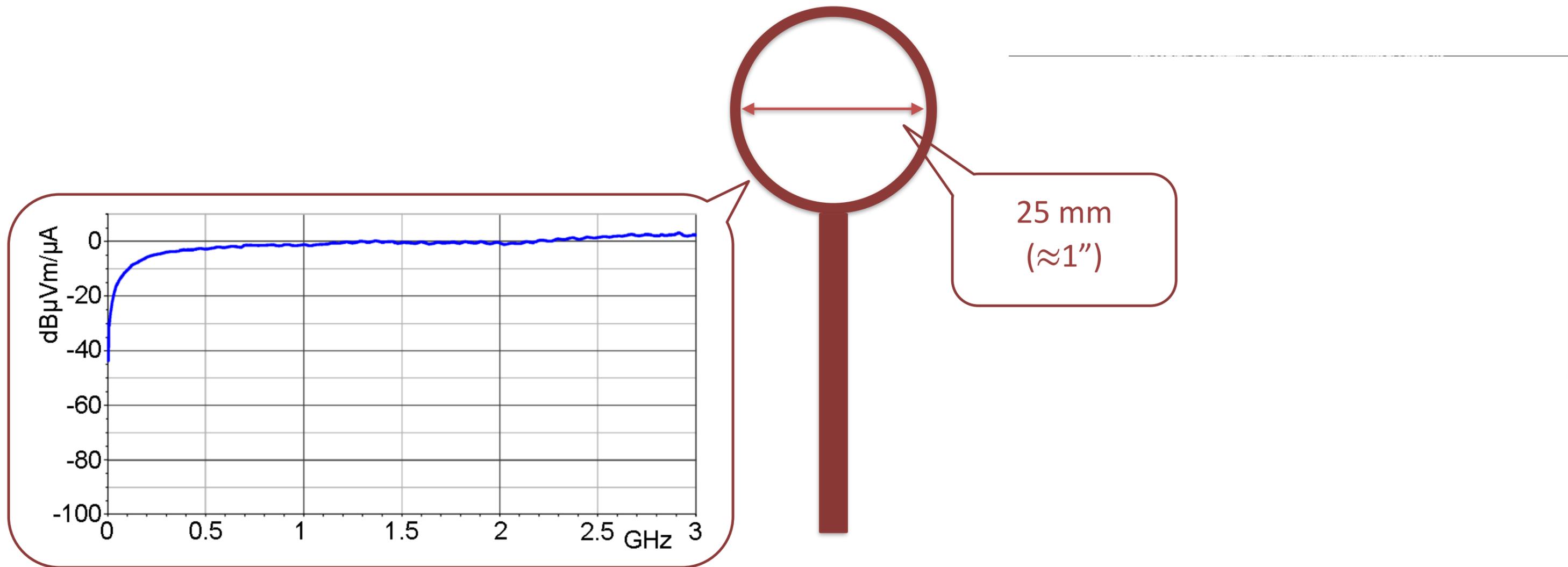
# Antenna Positioning

Langer RF-R 400

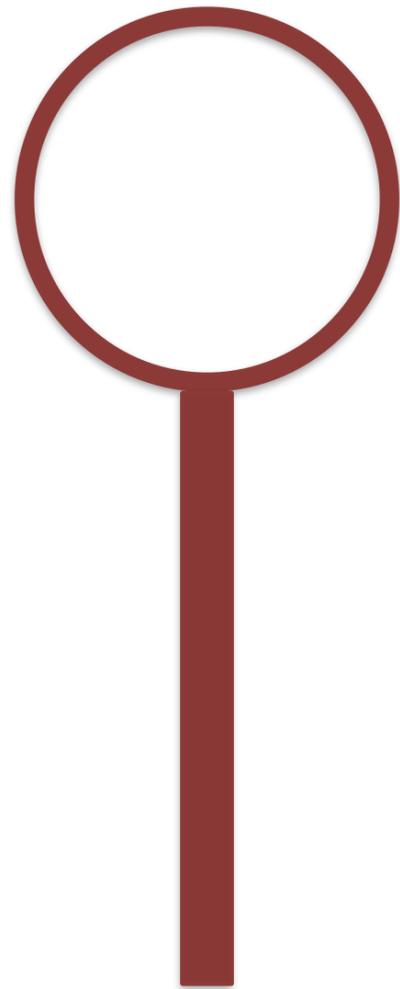


# Antenna Positioning

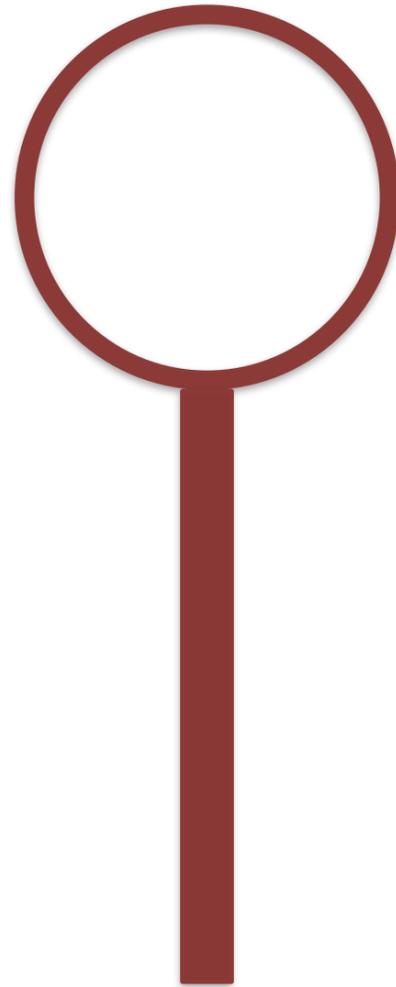
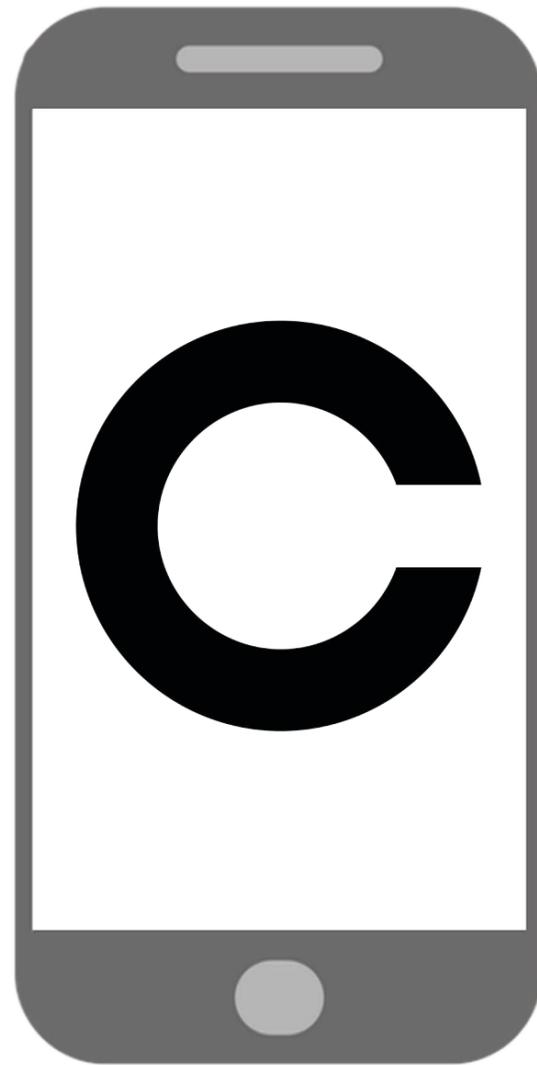
Langer RF-R 400



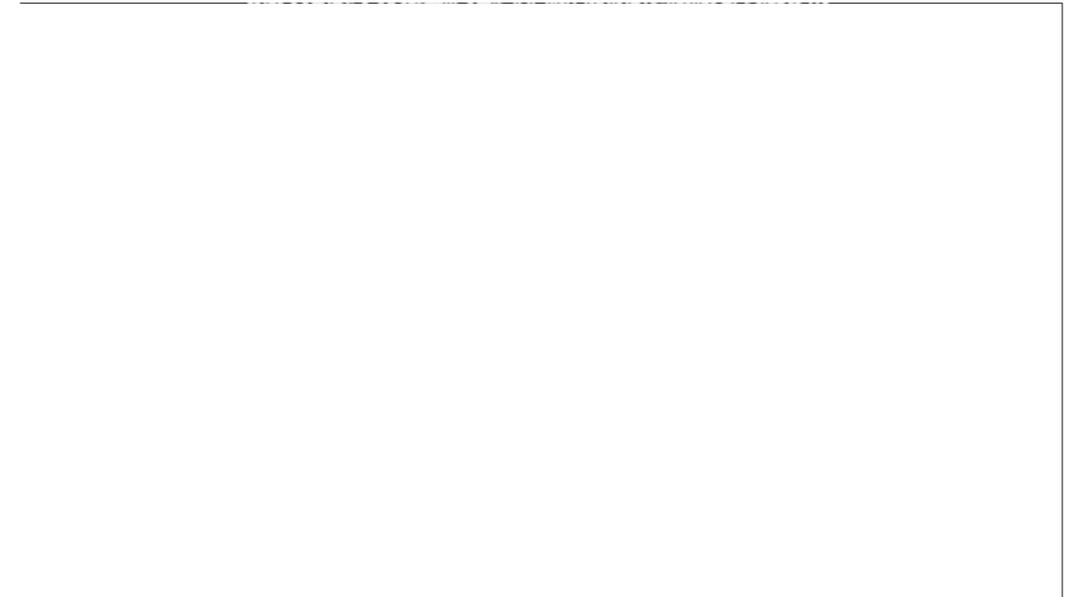
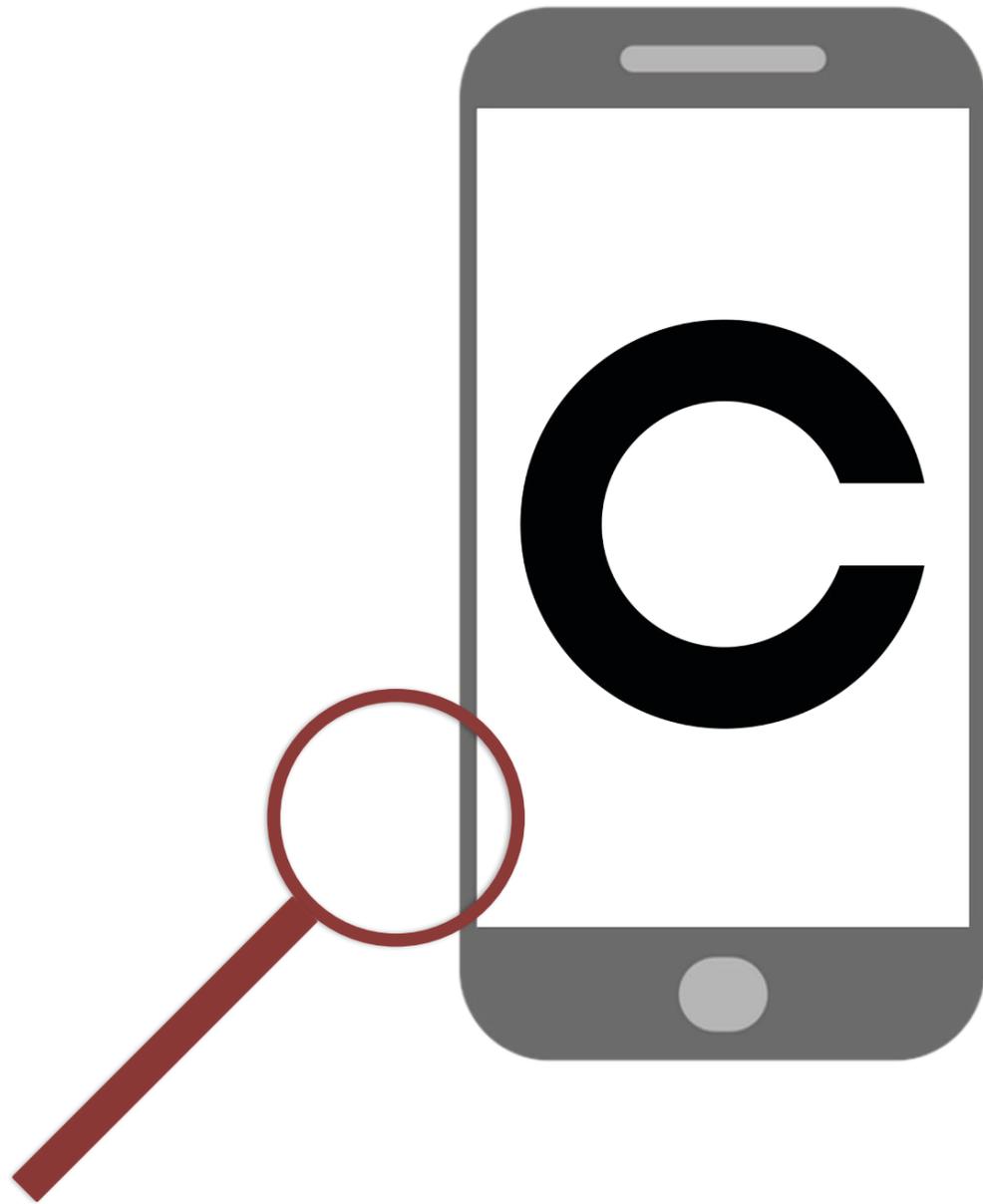
# Antenna Positioning



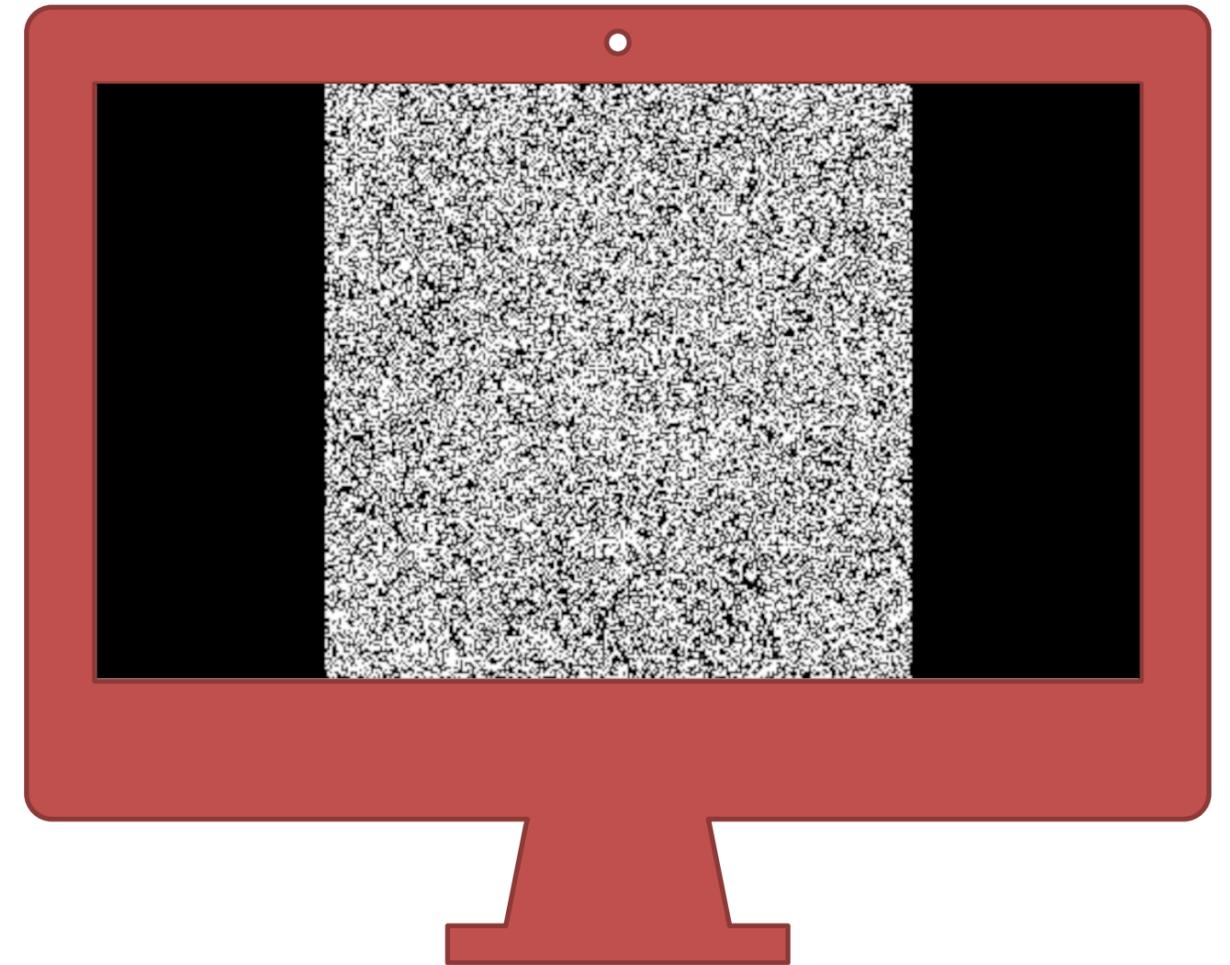
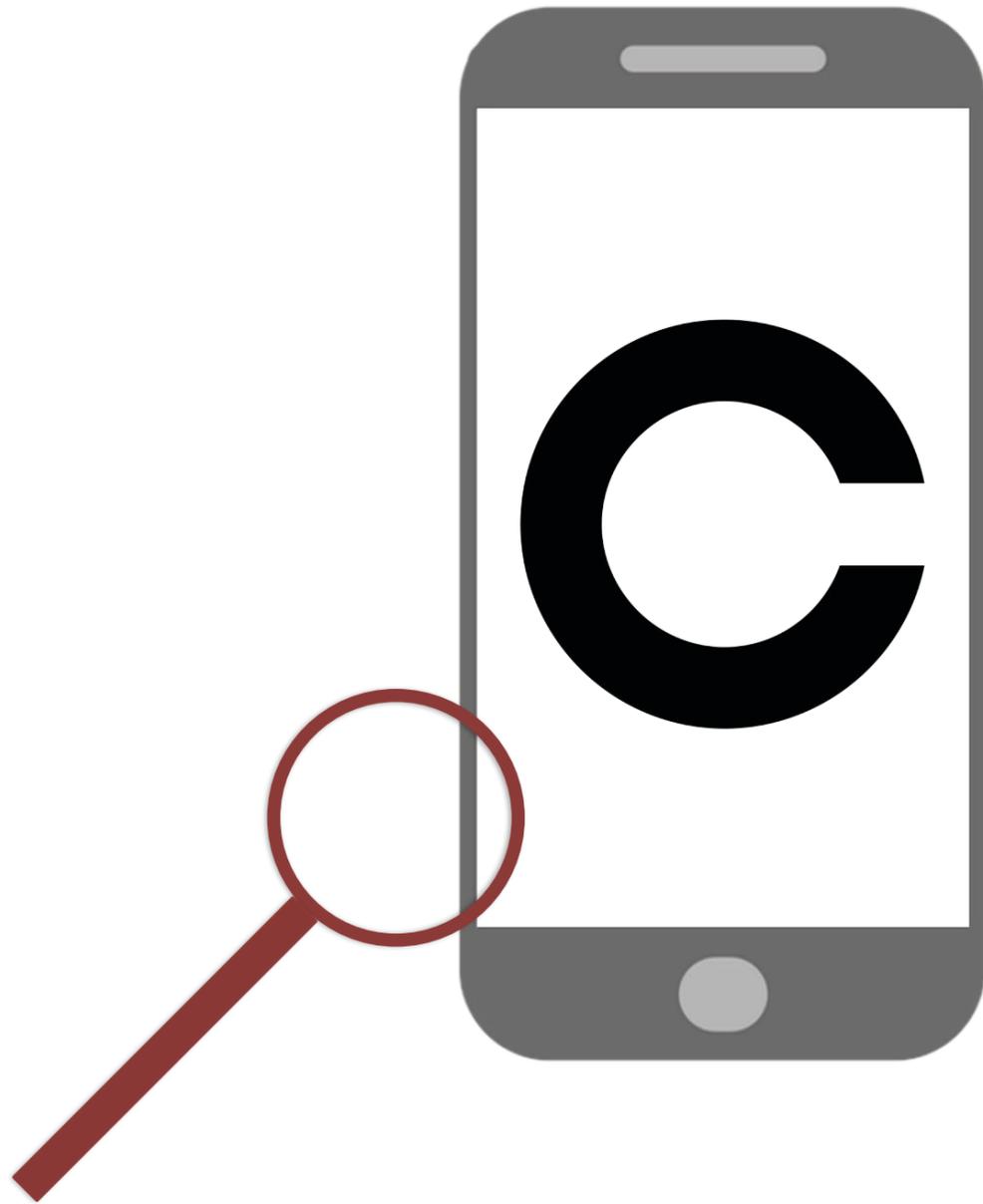
# Antenna Positioning



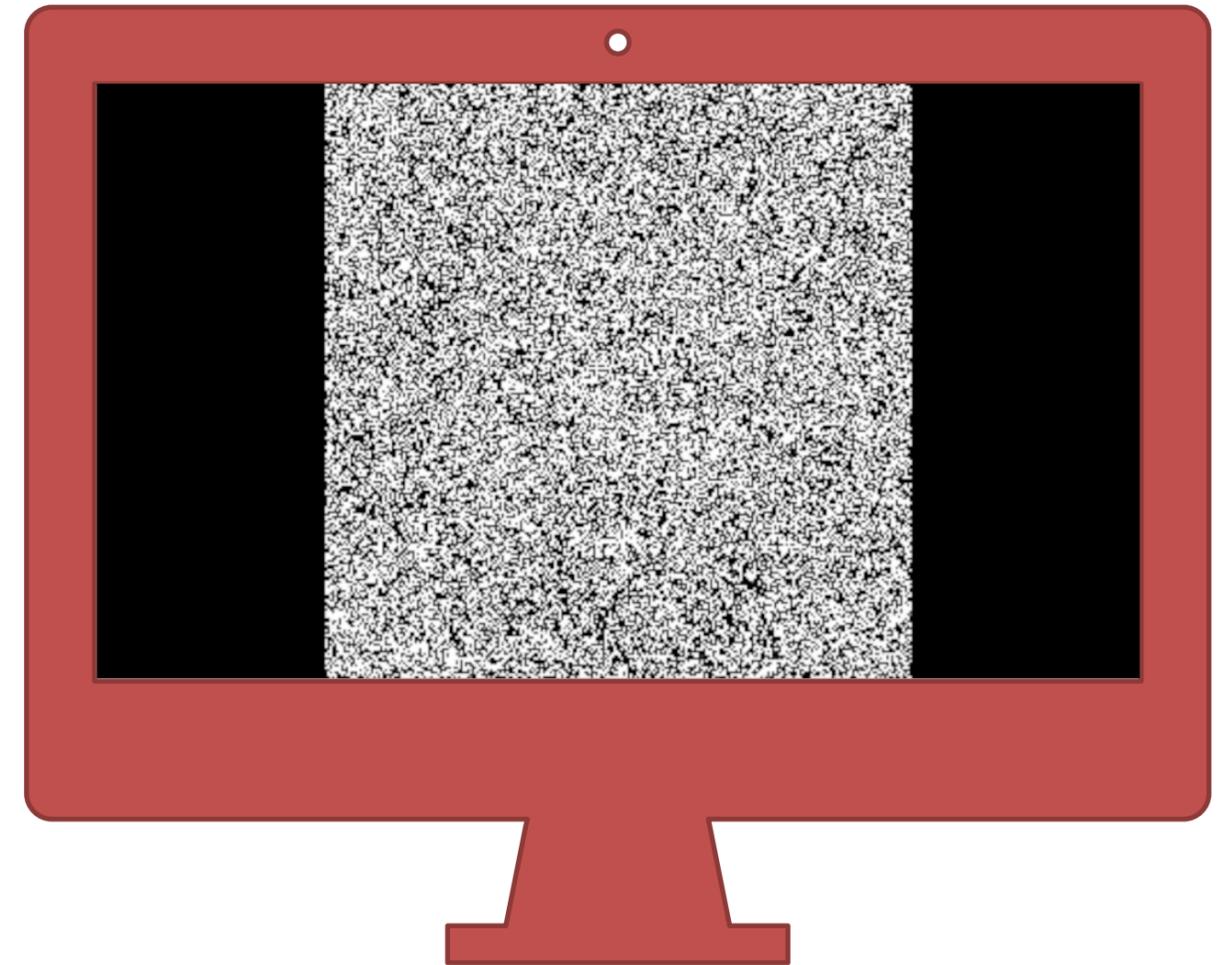
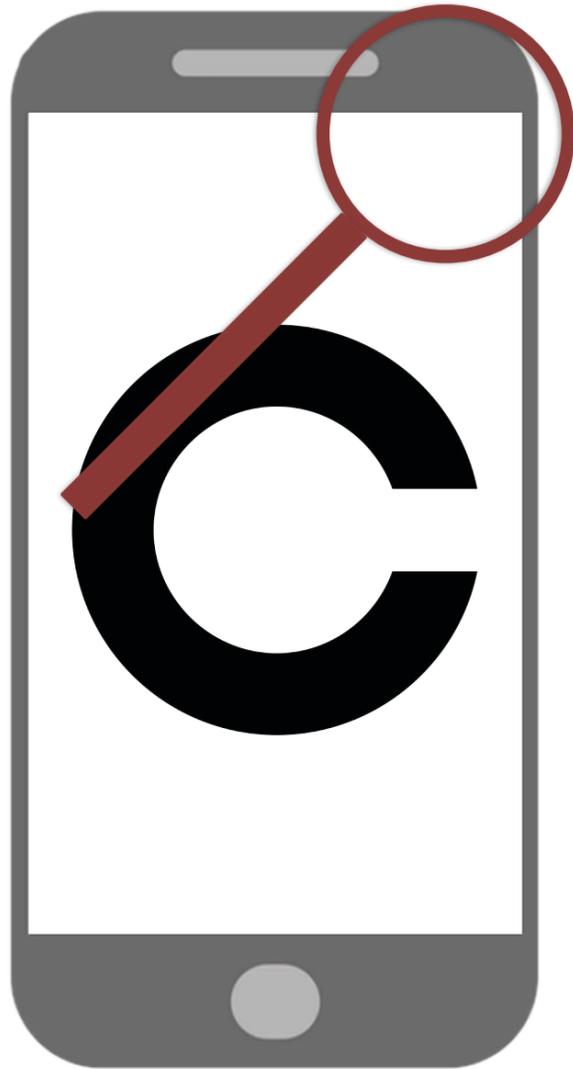
# Antenna Positioning



# Antenna Positioning



# Antenna Positioning



# Limitations

# Limitations

- Near-Field probes

# Limitations

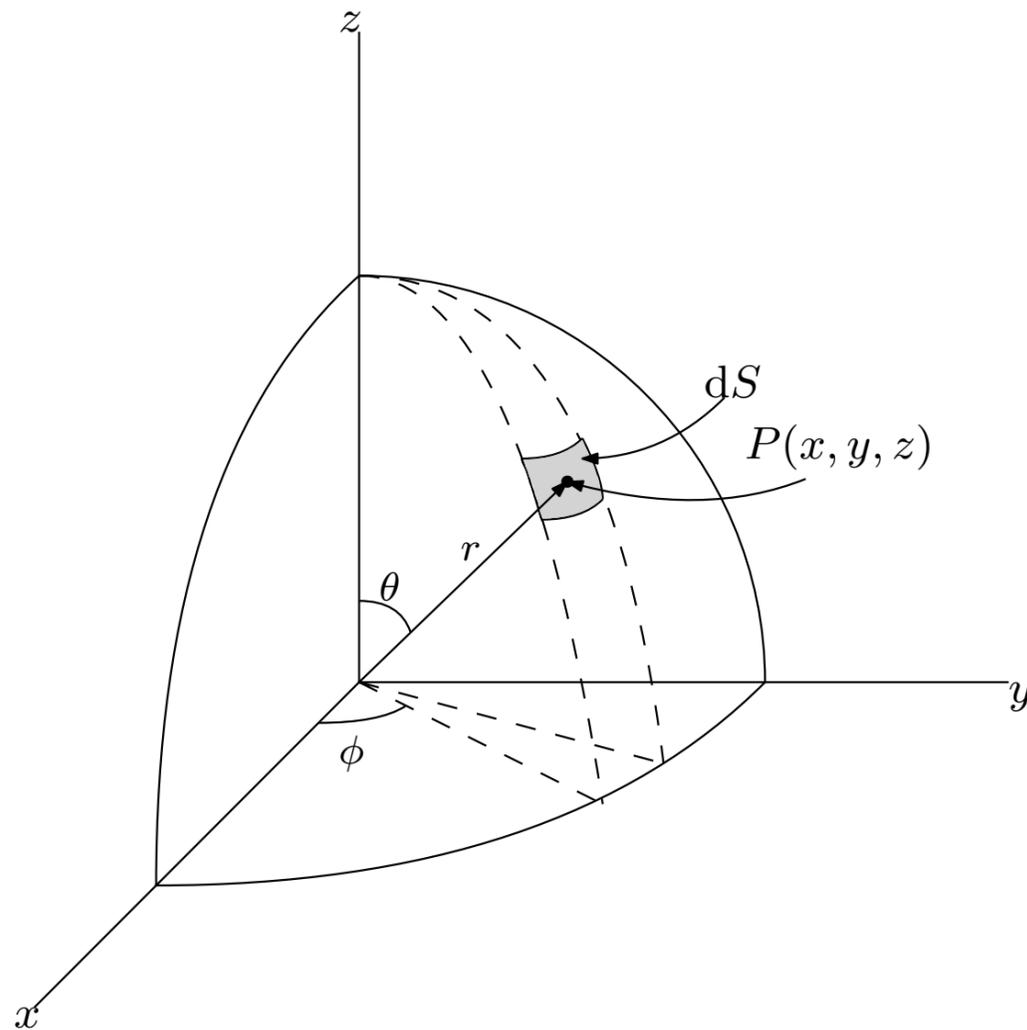
- Near-Field probes
  - Only for showing proof of concept

# Limitations

- Near-Field probes
  - Only for showing proof of concept
  - Inefficient for distances  $> 2$  cm

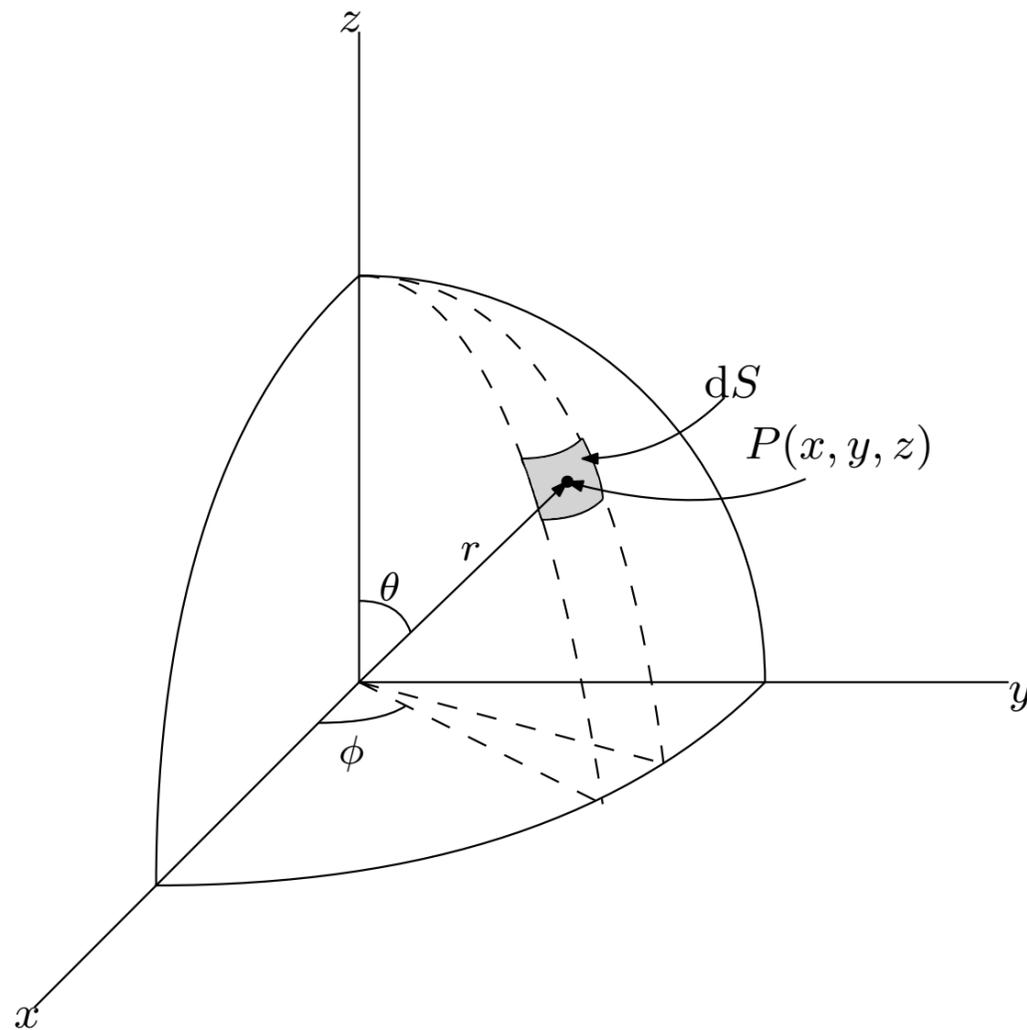
# Limitations

- Near-Field probes
  - Only for showing proof of concept
  - Inefficient for distances  $> 2$  cm



# Limitations

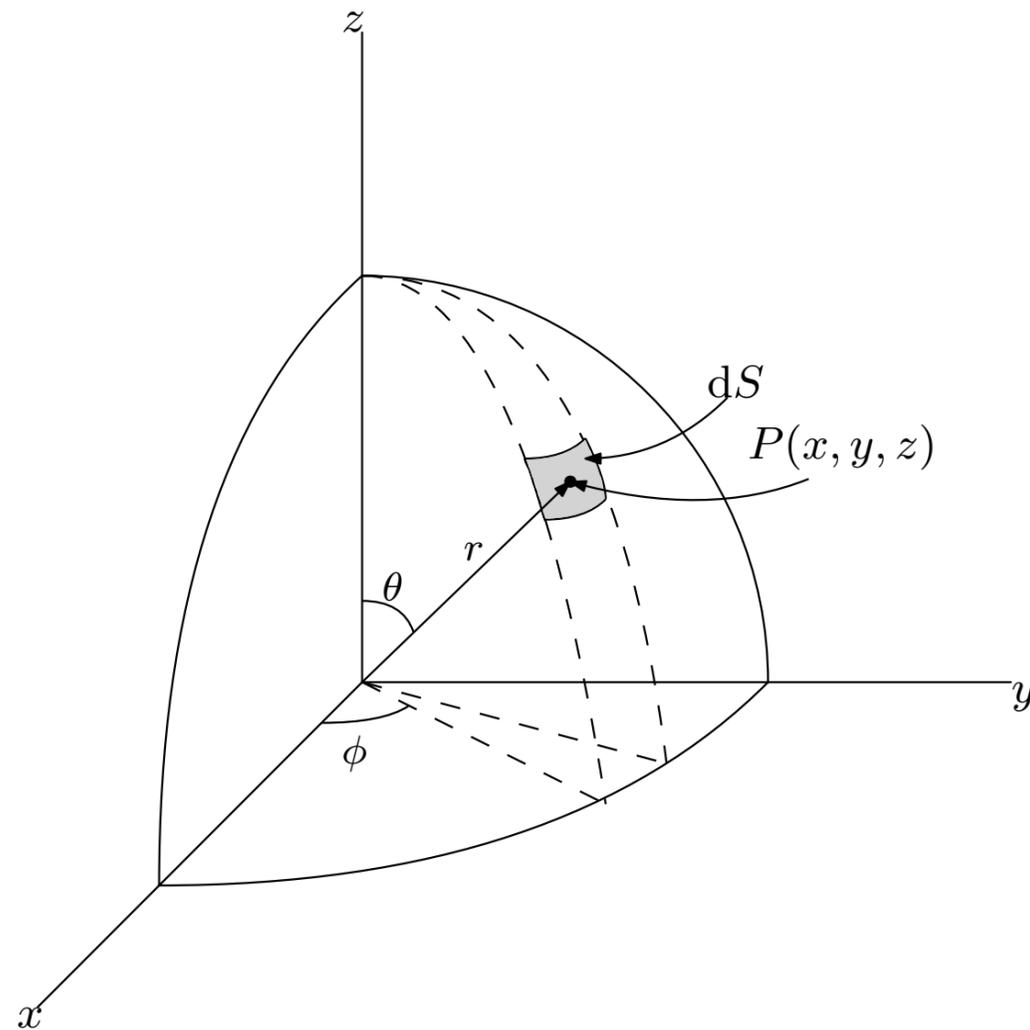
- Near-Field probes
  - Only for showing proof of concept
  - Inefficient for distances  $> 2$  cm



$$\mathcal{P}_{av} = \vec{e}_r \frac{j\omega\mu m^2}{16\pi r^5} \sin^2 \theta - \vec{e}_\theta \frac{j\omega\mu m^2}{8\pi r^5} \sin \theta \cos \theta$$

# Limitations

- Near-Field probes
  - Only for showing proof of concept
  - Inefficient for distances  $> 2$  cm



$$\mathcal{P}_{av} = \vec{e}_r \frac{j\omega\mu m^2}{16\pi r^5} \sin^2 \theta - \vec{e}_\theta \frac{j\omega\mu m^2}{8\pi r^5} \sin \theta \cos \theta$$

$m$  := magnetic moment of loop

$\mu$  := magnetic permeability

$\omega$  := angular frequency (i.e.,  $\omega = 2\pi f$ )

# Signal Strength

# Signal Strength



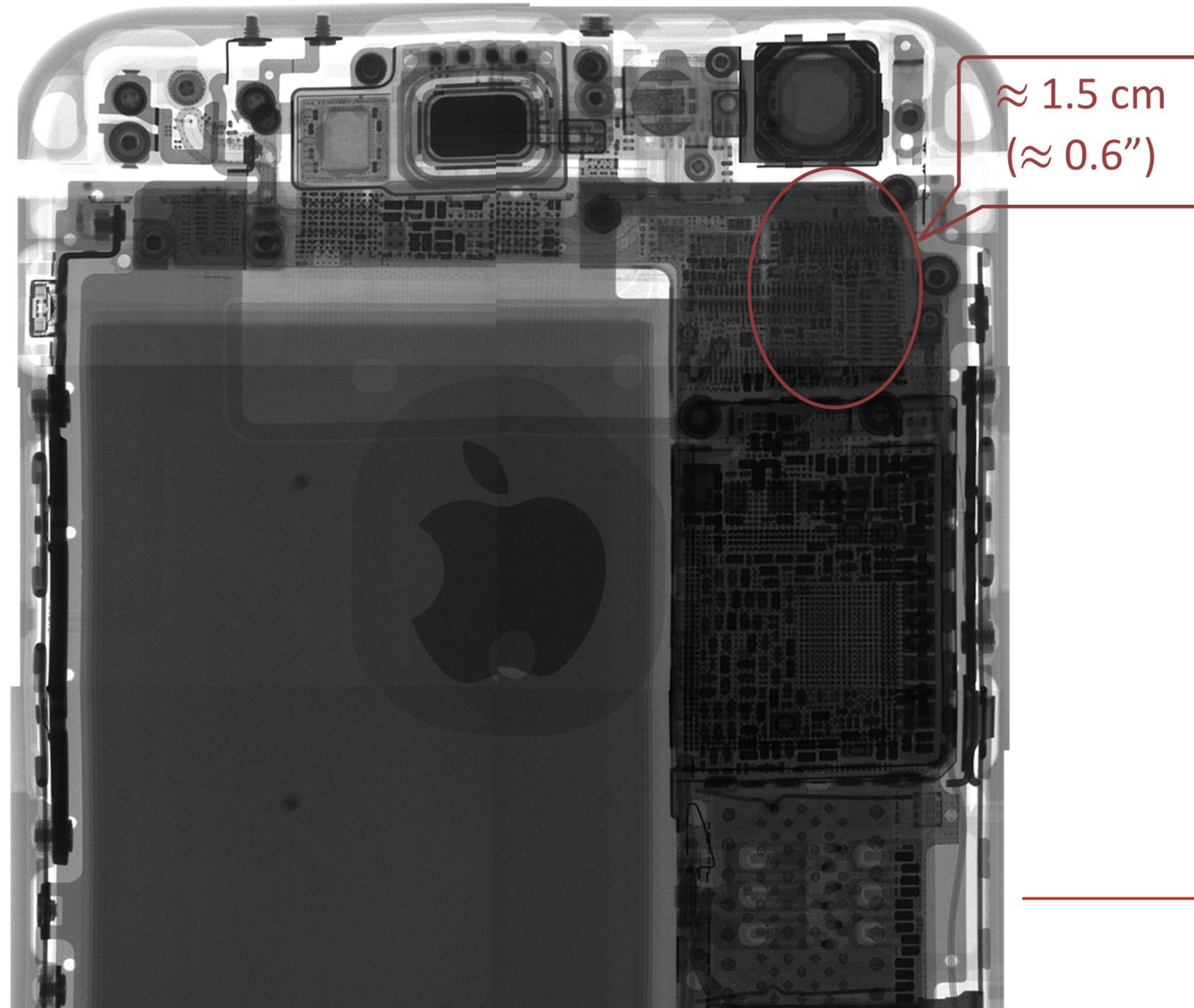
iPhone 6(s)

# Signal Strength



iPhone 6(s)

# Signal Strength



iPhone 6(s)

# Signal Strength

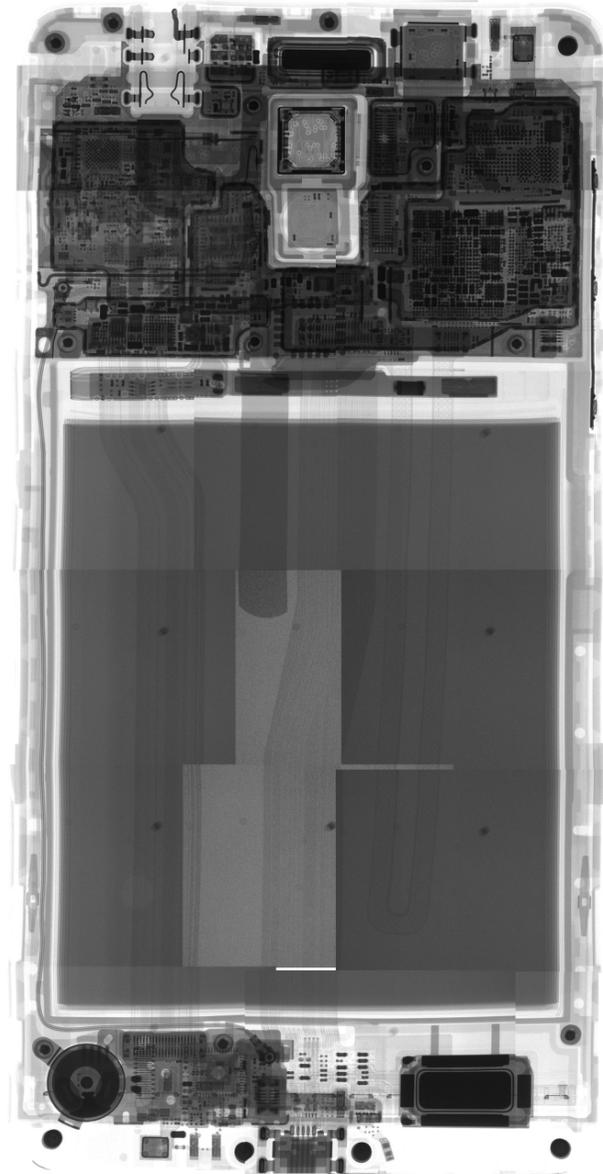


iPhone 6(s)

# Signal Strength



iPhone 6(s)

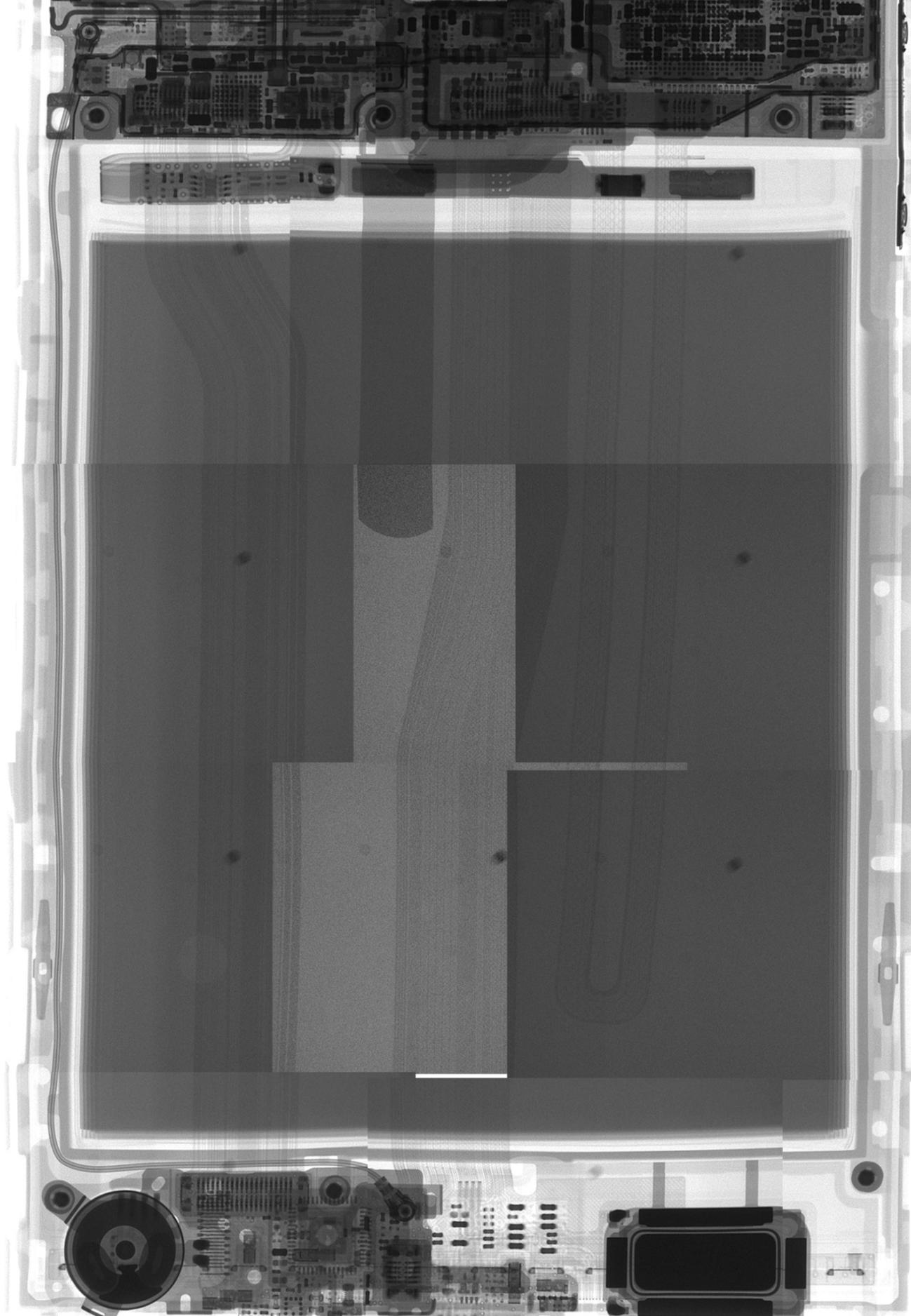


Honor 6X

# Signal Strength



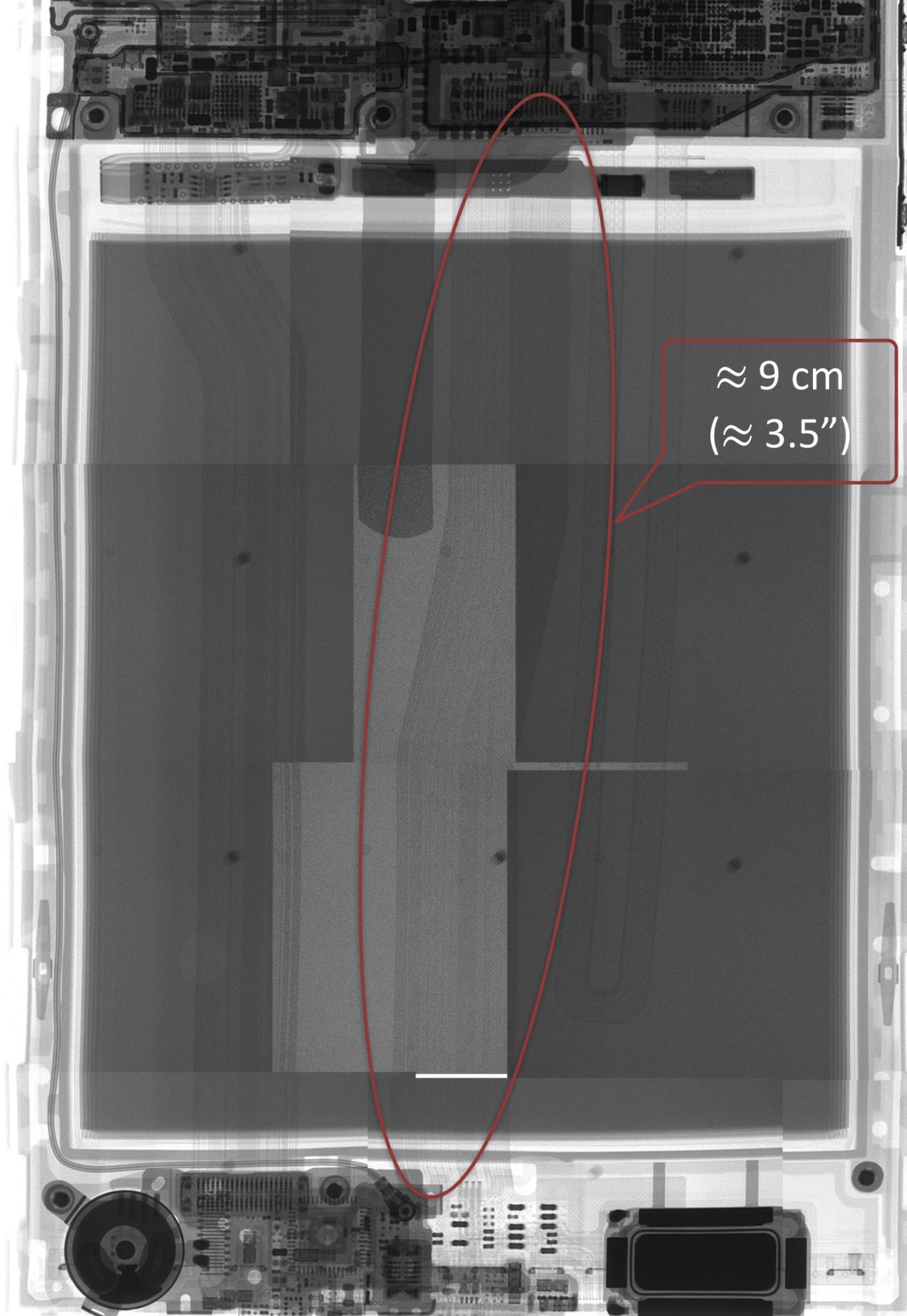
iPhone 6(s)



# Signal Strength



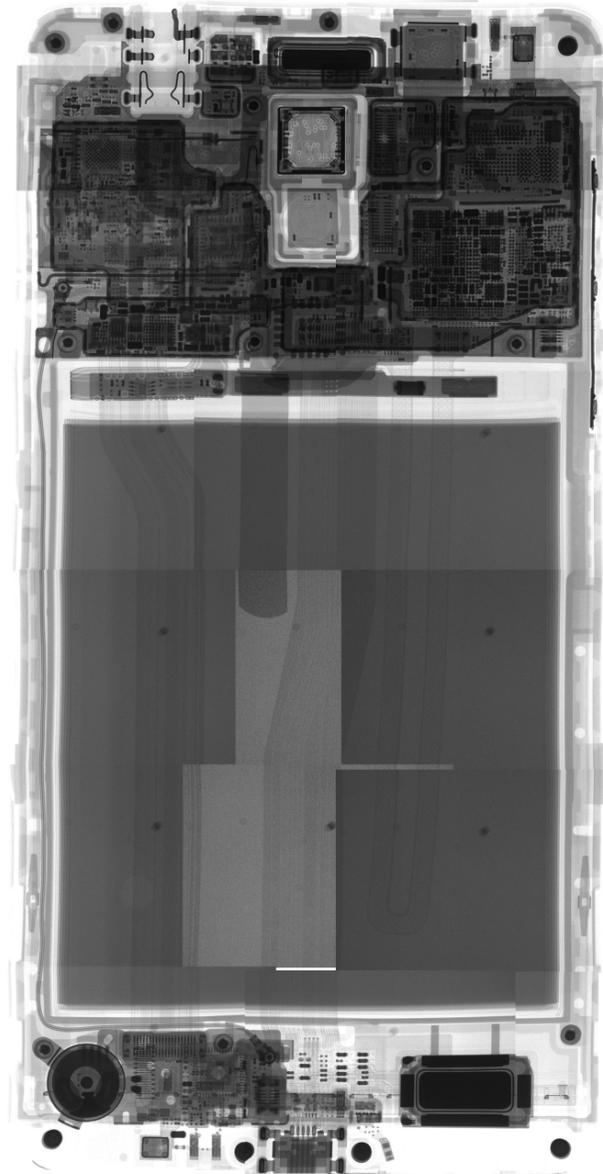
iPhone 6(s)



# Signal Strength



iPhone 6(s)

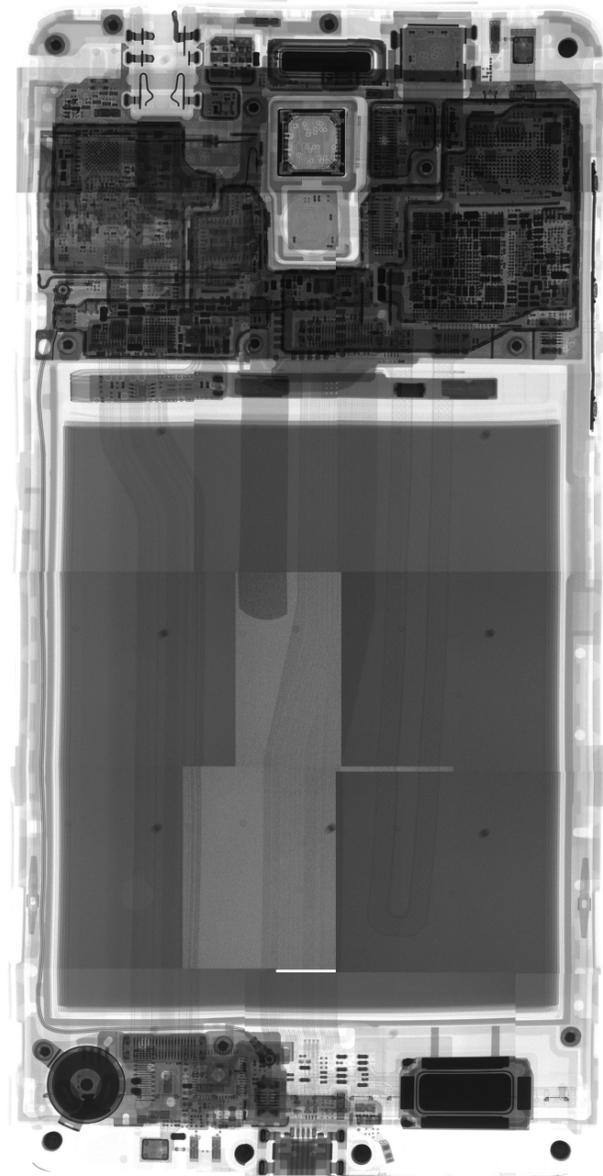


Honor 6X

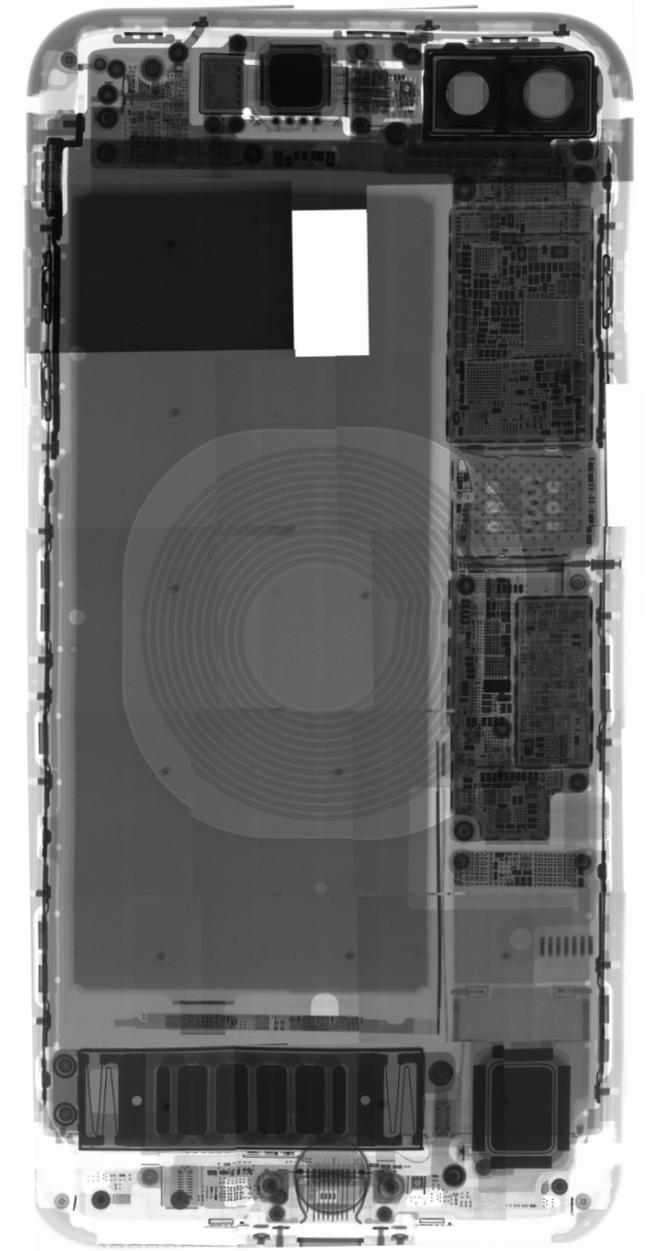
# Signal Strength



iPhone 6(s)



Honor 6X

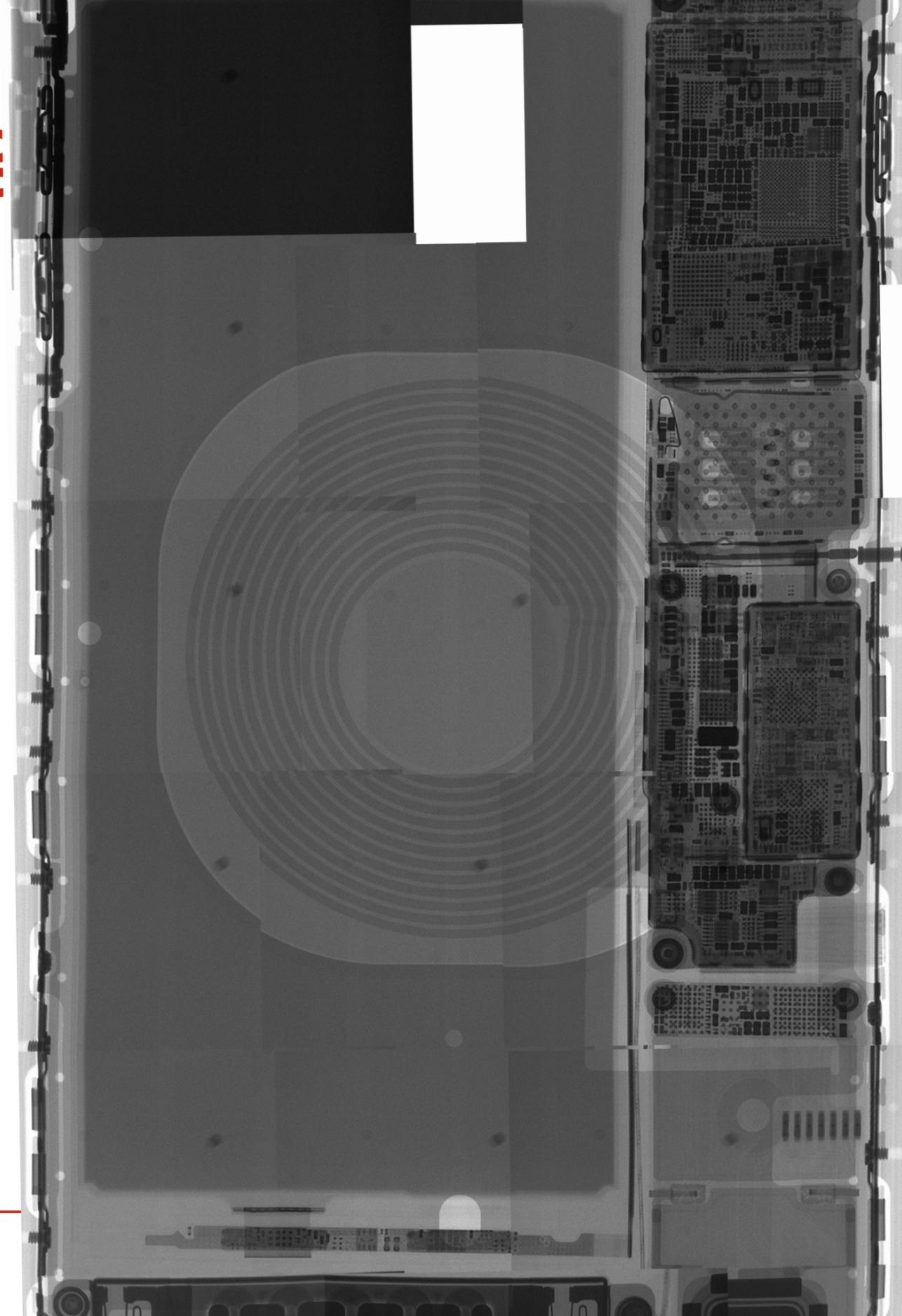


iPhone 8 Plus

# Signal Strength



iPhone 6(s)

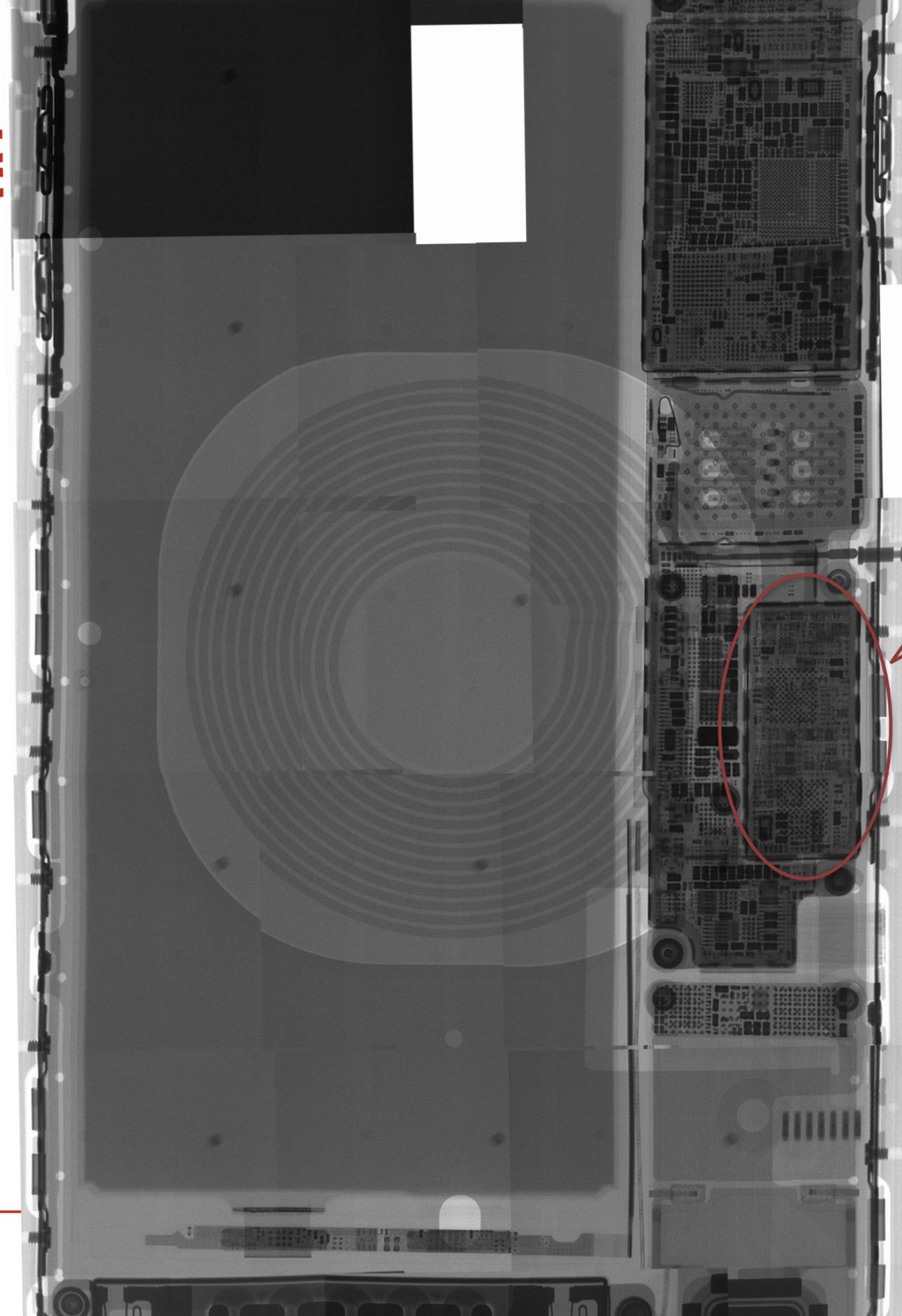


iPhone 8 Plus

# Signal Strength



iPhone 6(s)

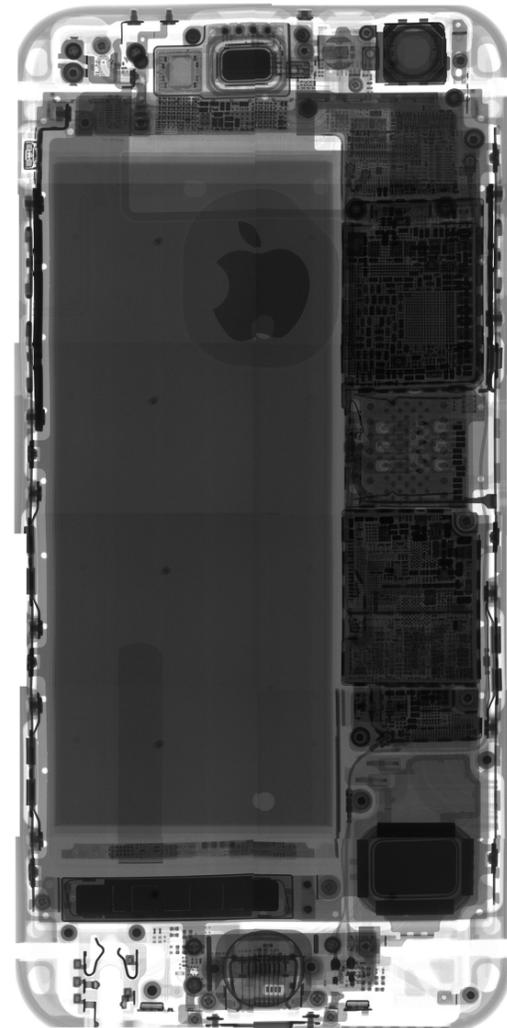


≈ 0.5 cm  
(≈ 0.2")

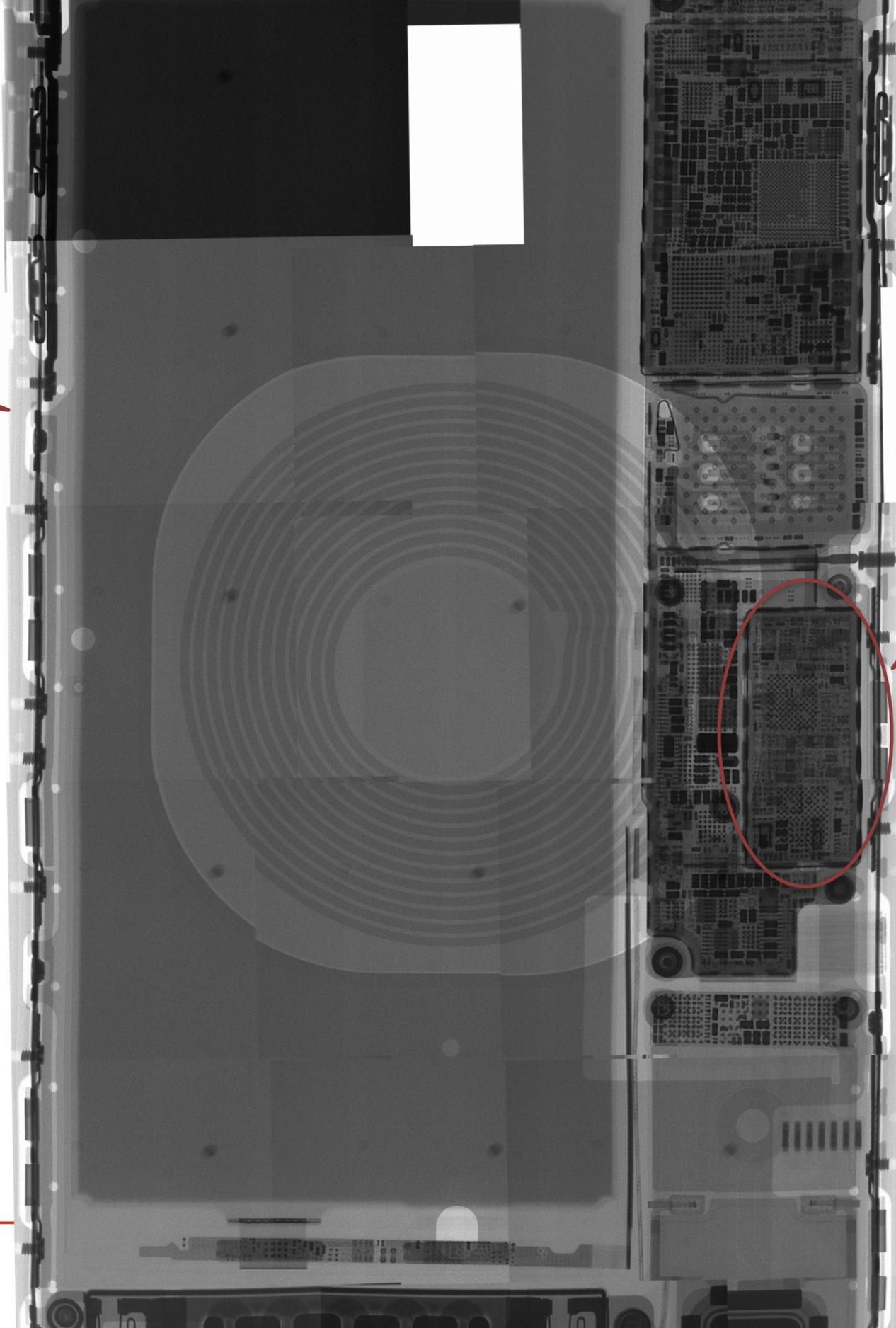
iPhone 8 Plus

# Signal Strength

Better shielding  
(More power to X-ray)



iPhone 6(s)



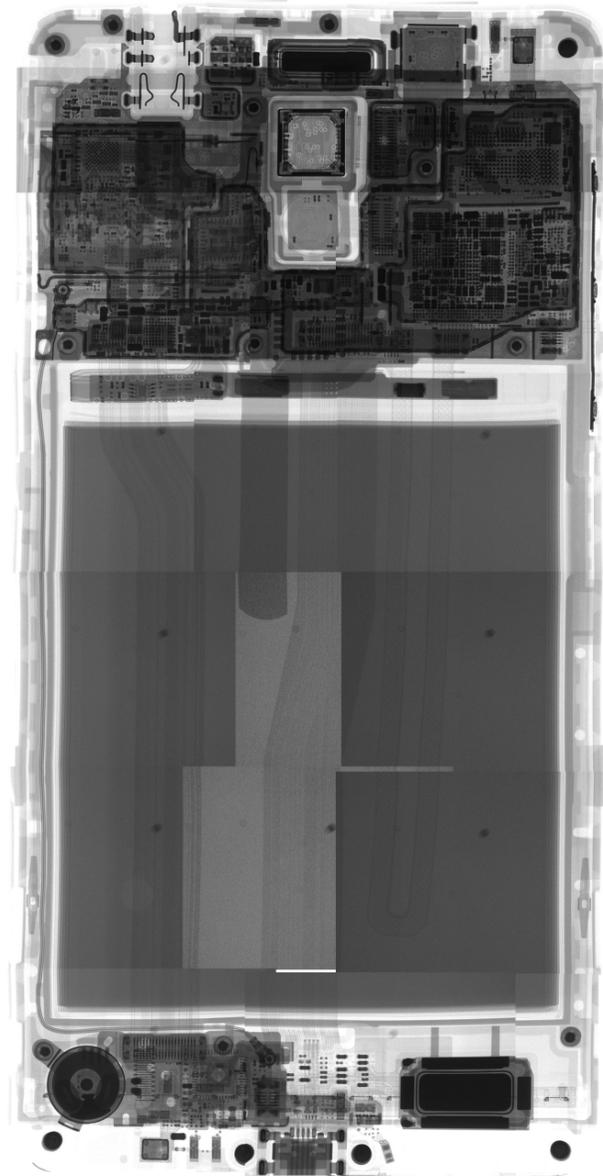
$\approx 0.5$  cm  
( $\approx 0.2$ " )

iPhone 8 Plus

# Signal Strength



iPhone 6(s)



Honor 6X



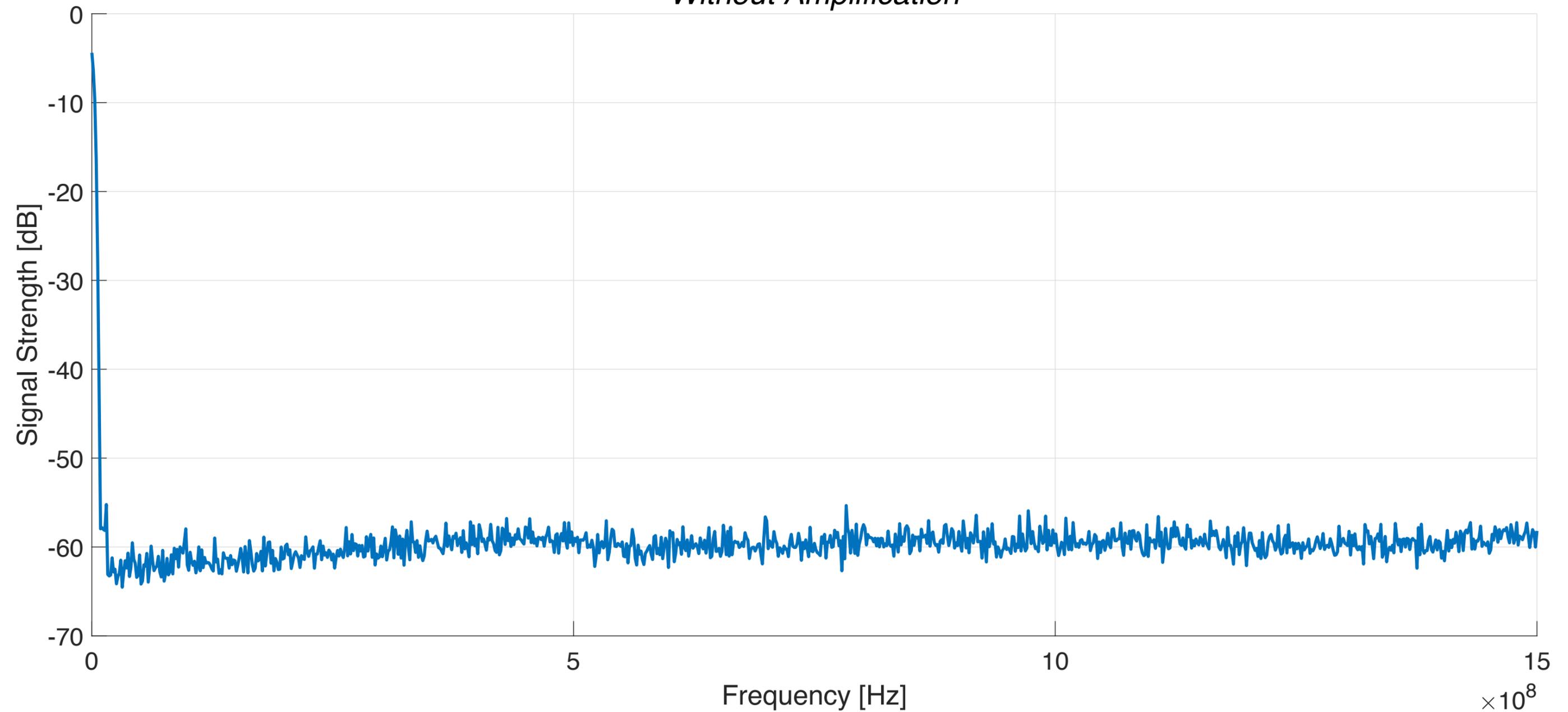
iPhone 8 Plus

# Amplification

# Amplification

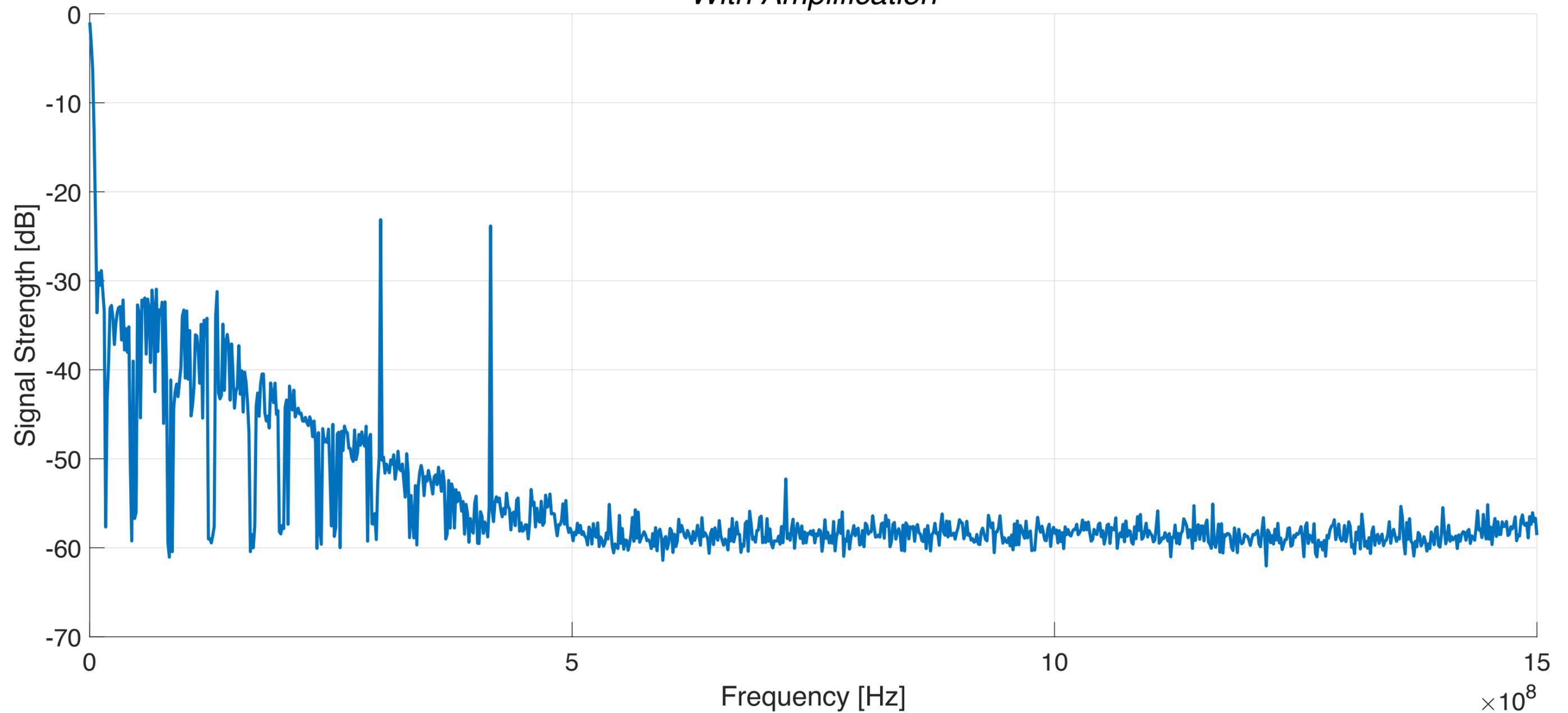
## Frequency Spectrum of an iPhone 6 Display Cable

*Without Amplification*

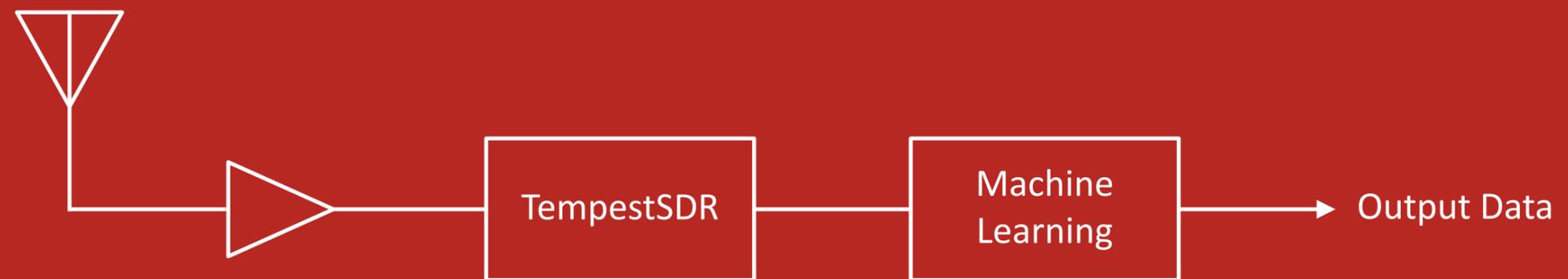
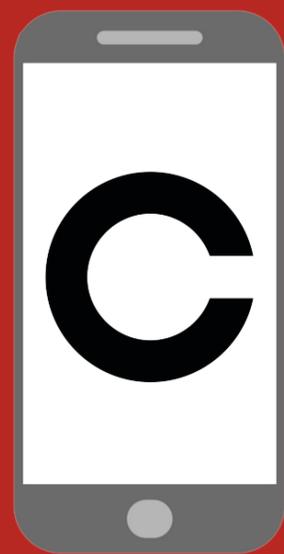


# Amplification

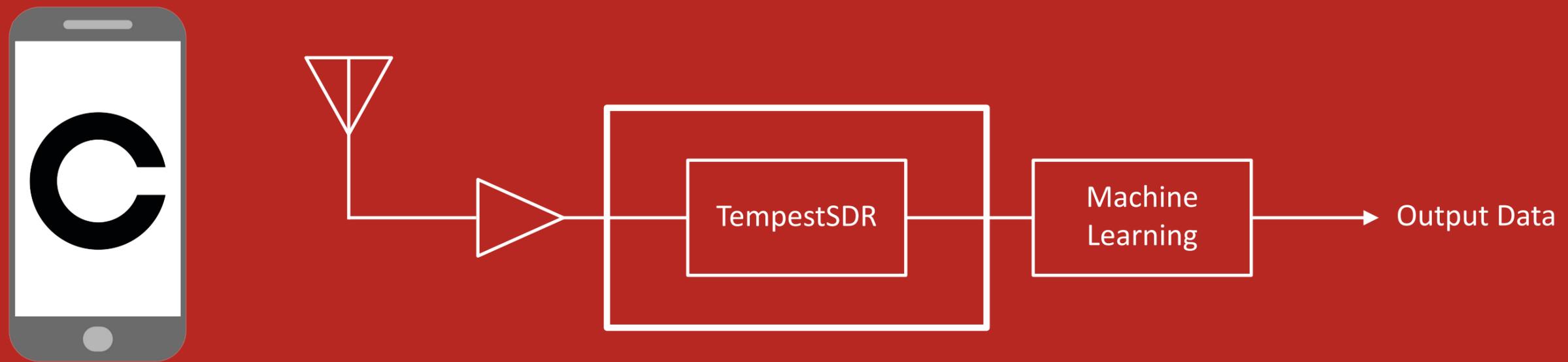
Frequency Spectrum of an iPhone 6 Display Cable  
*With Amplification*



# TempestSDR

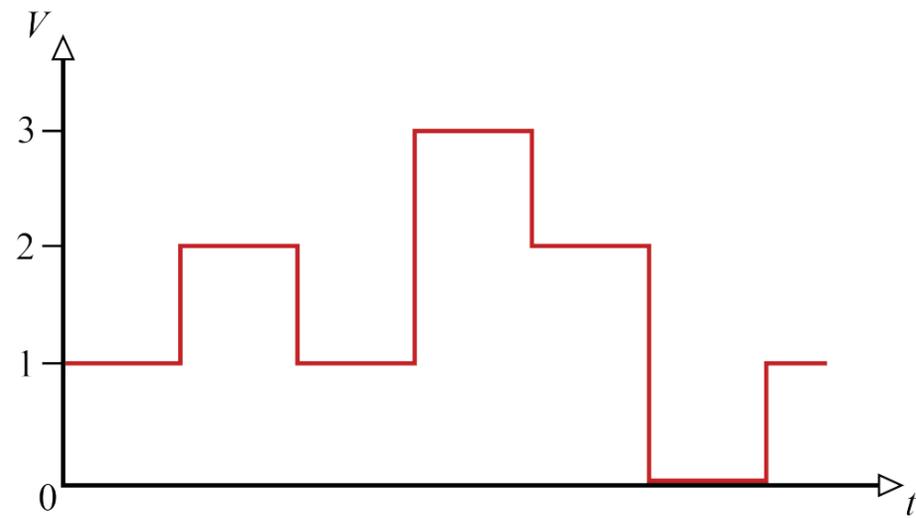


# TempestSDR

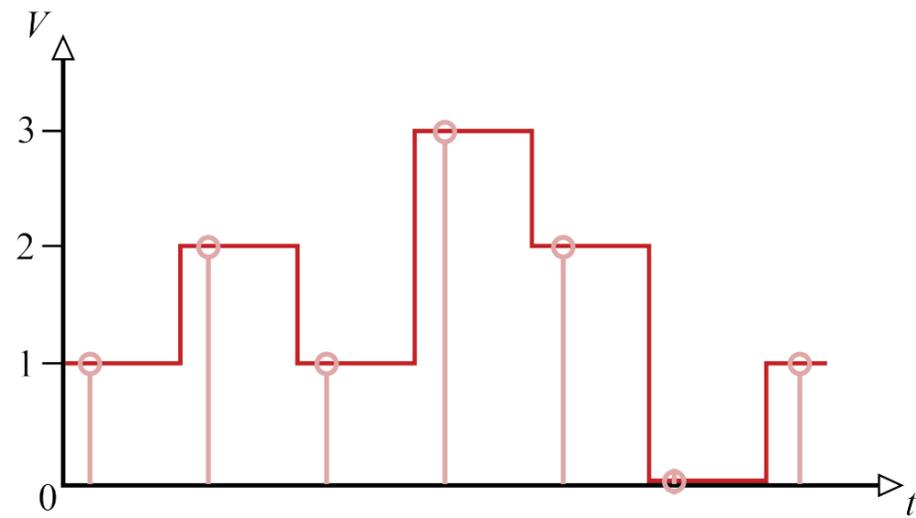


# Schematic Design

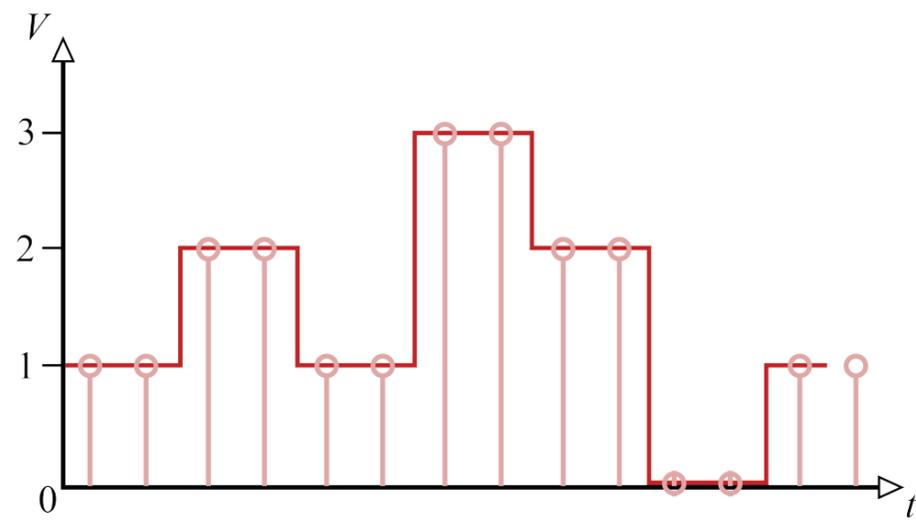
# Schematic Design



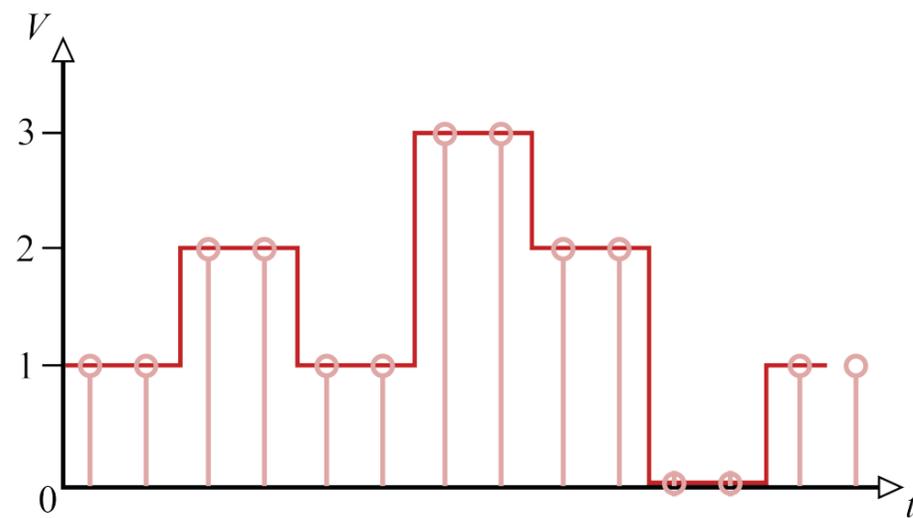
# Schematic Design



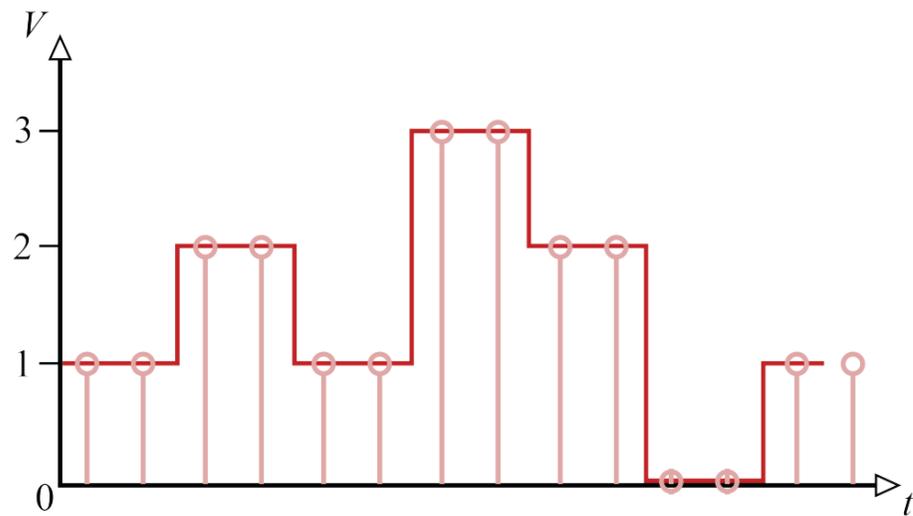
# Schematic Design



# Schematic Design

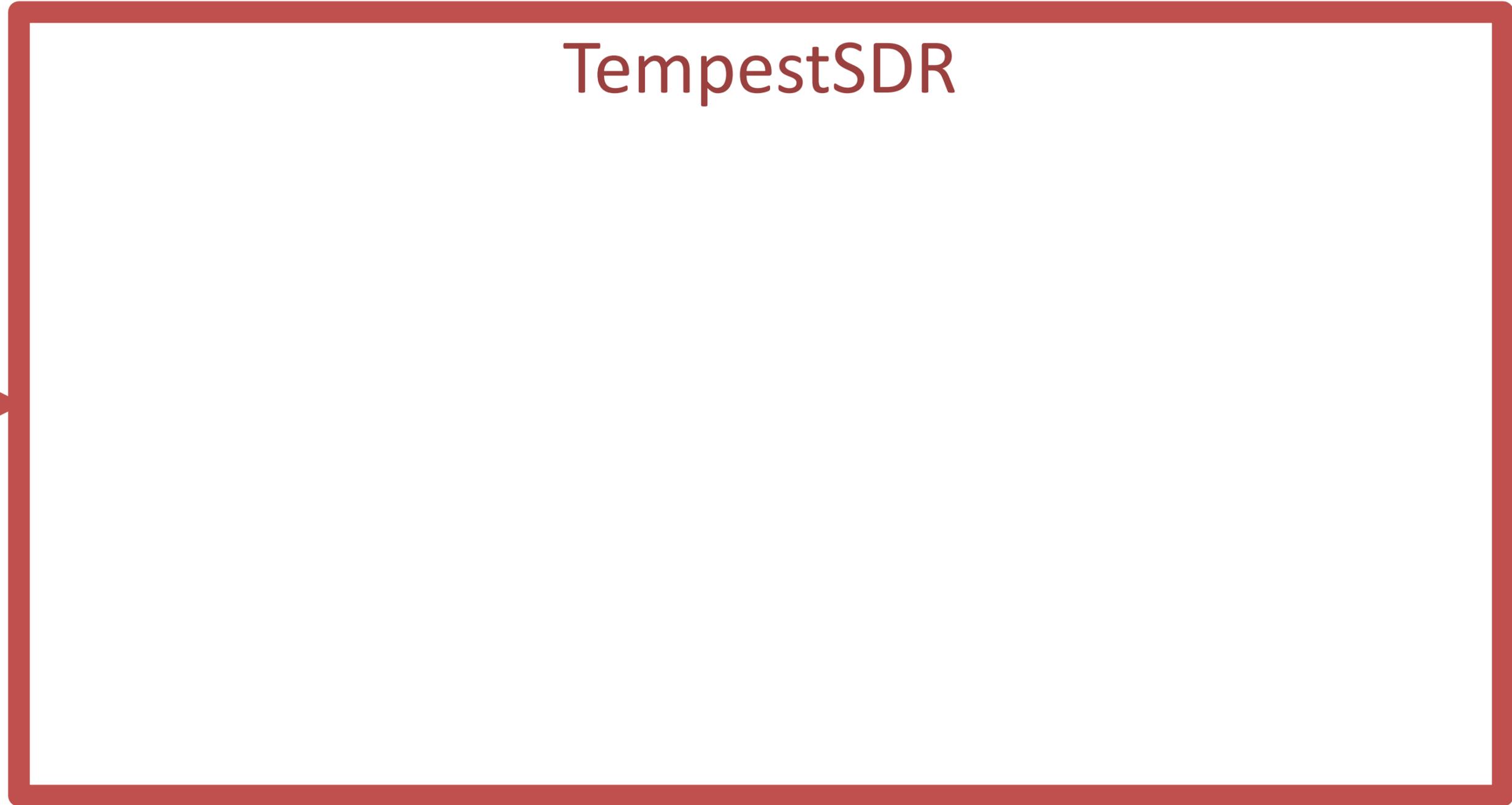
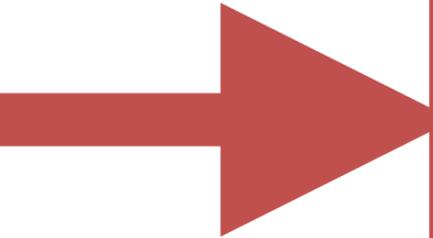


# Schematic Design



# Schematic Design

TempestSDR



# Schematic Design

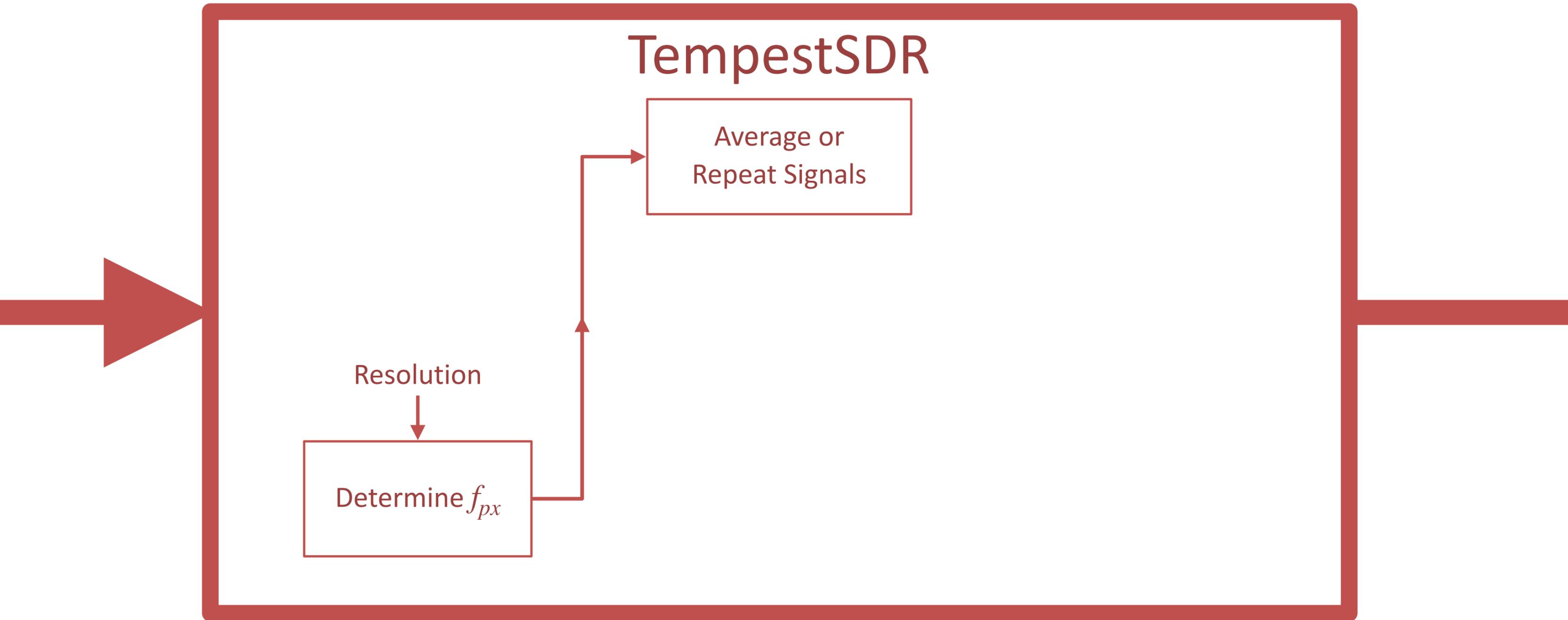
TempestSDR

Resolution

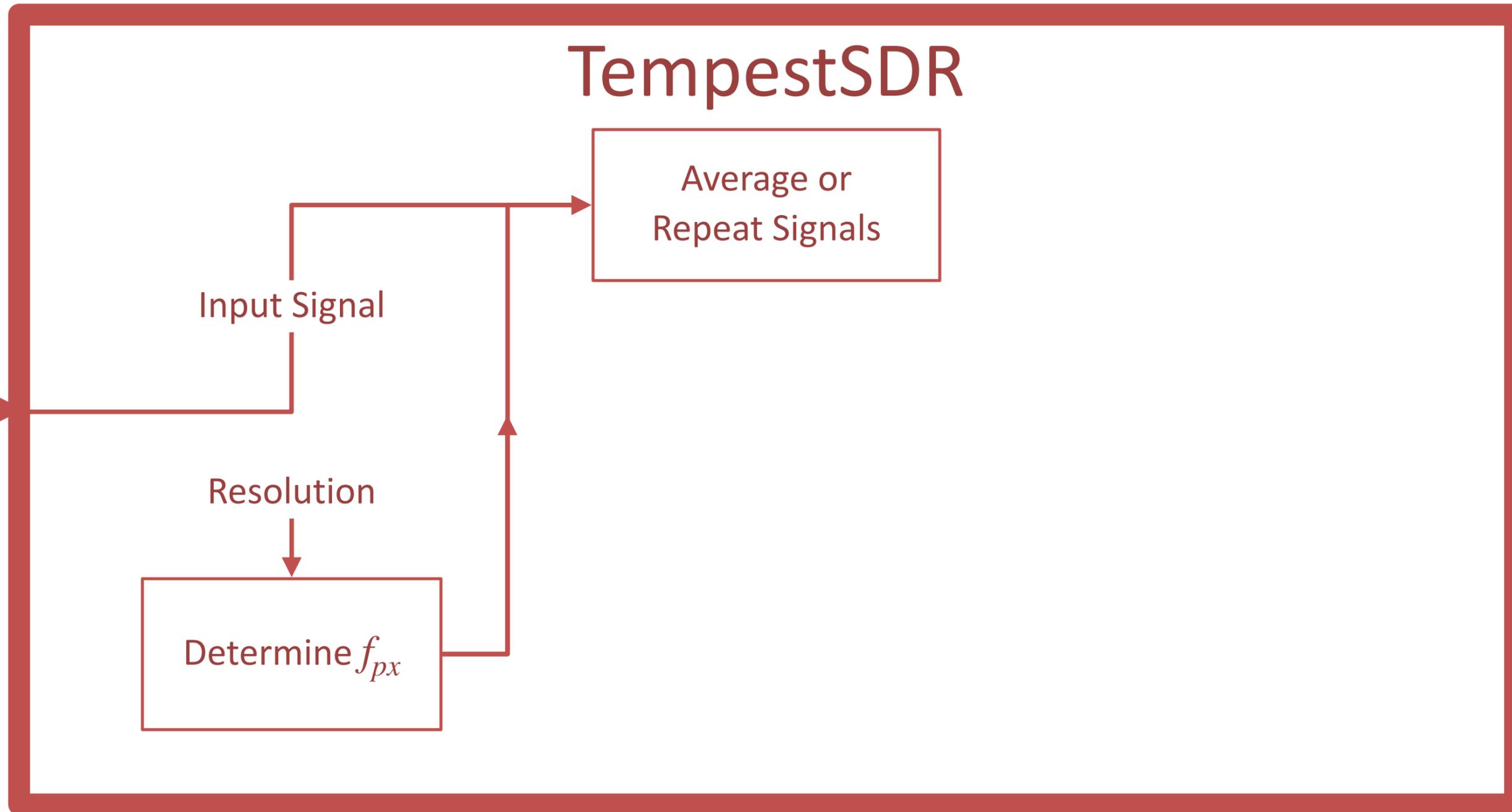


Determine  $f_{px}$

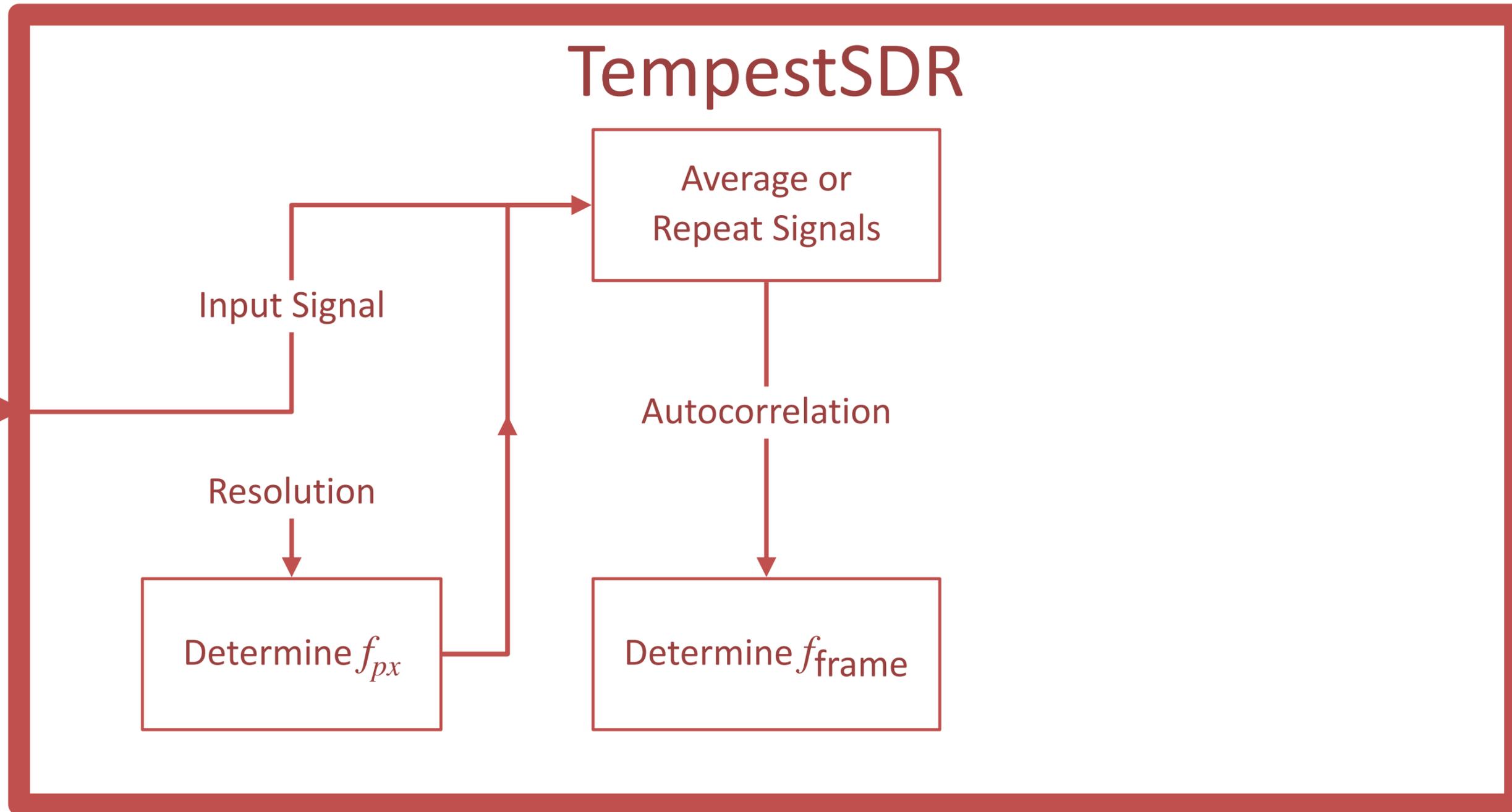
# Schematic Design



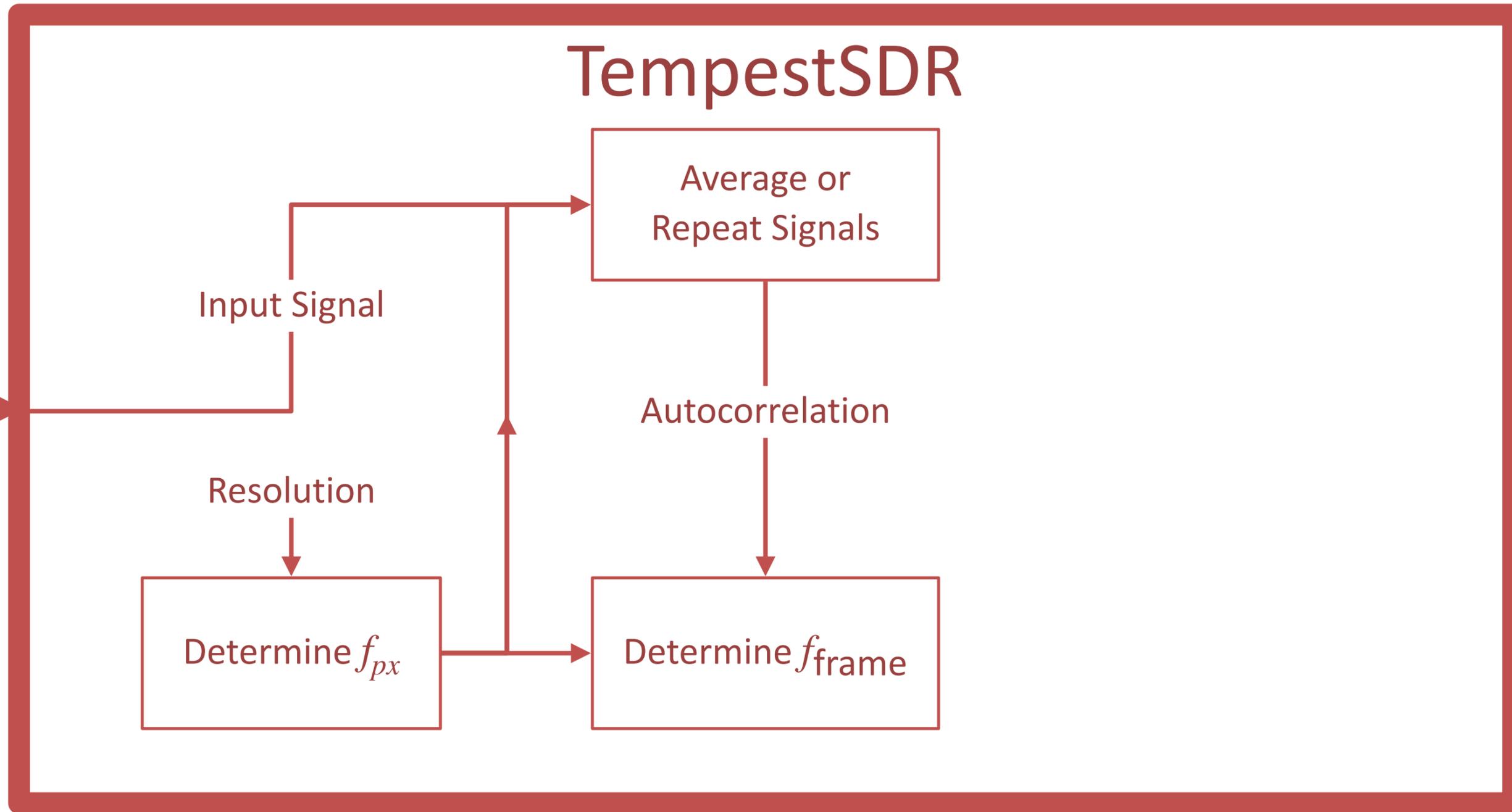
# Schematic Design



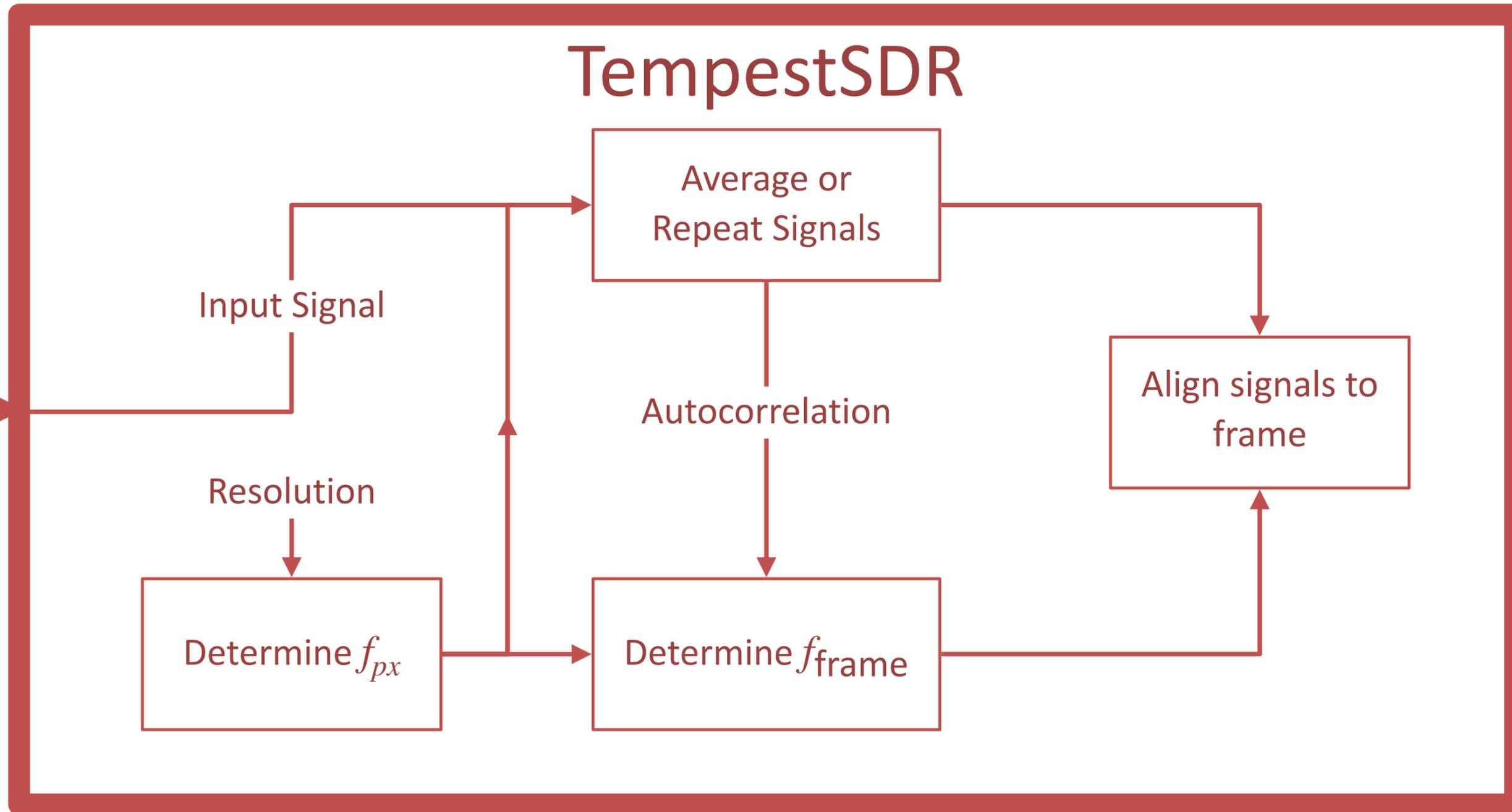
# Schematic Design



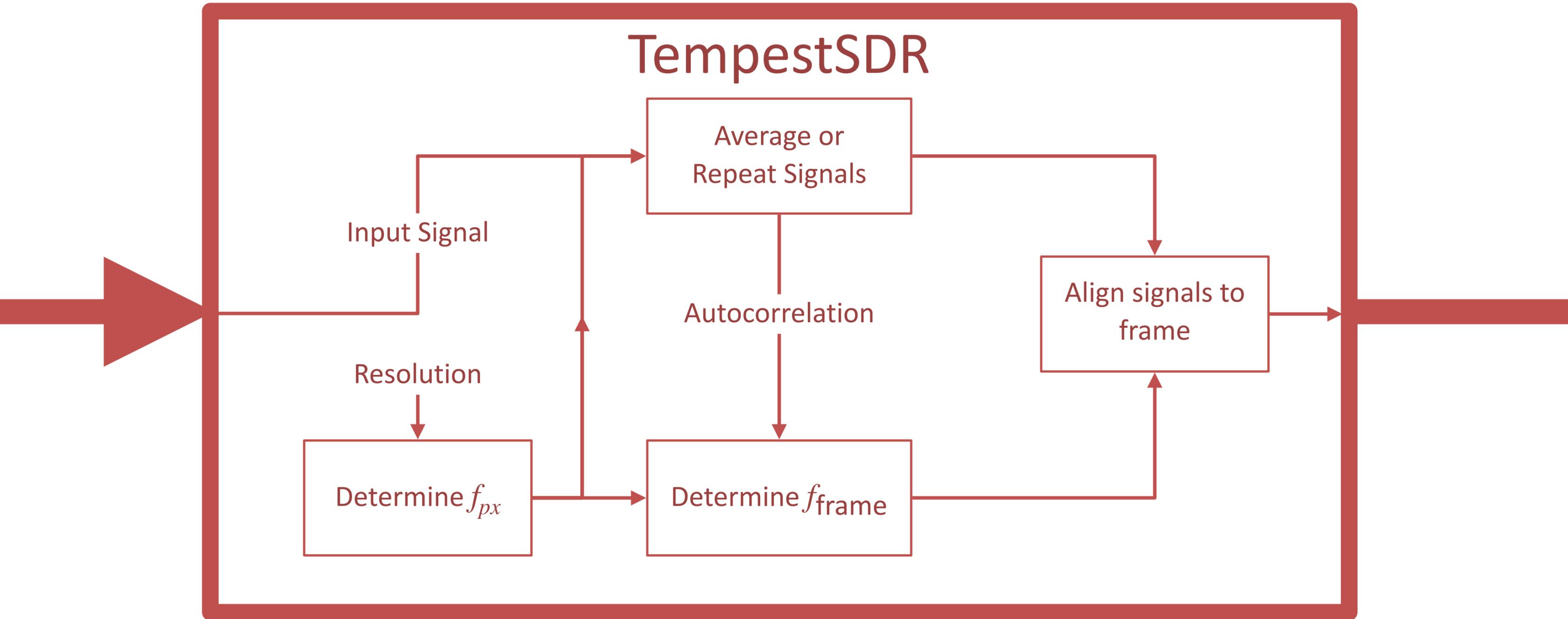
# Schematic Design



# Schematic Design

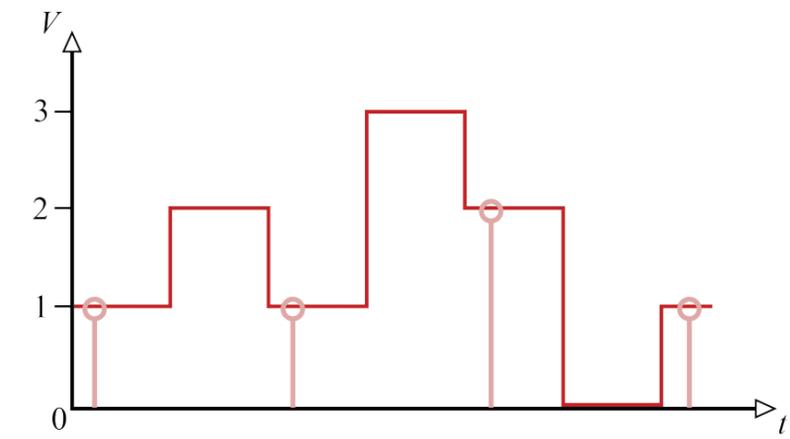


# Schematic Design

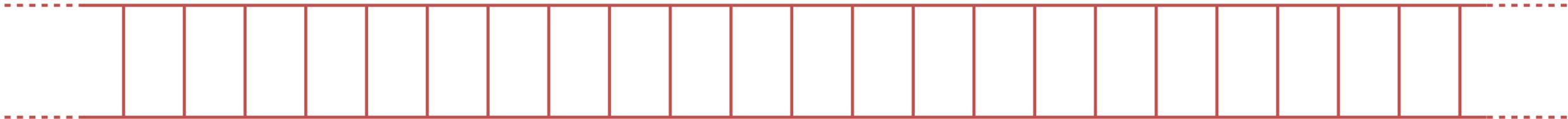
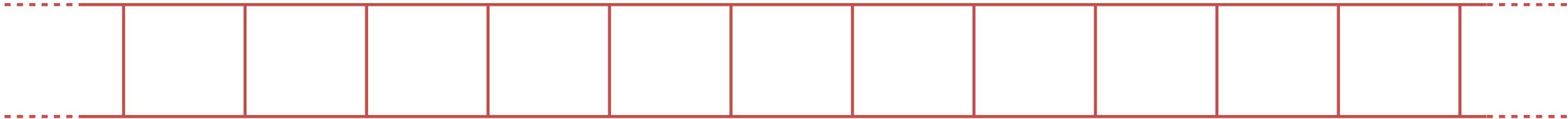
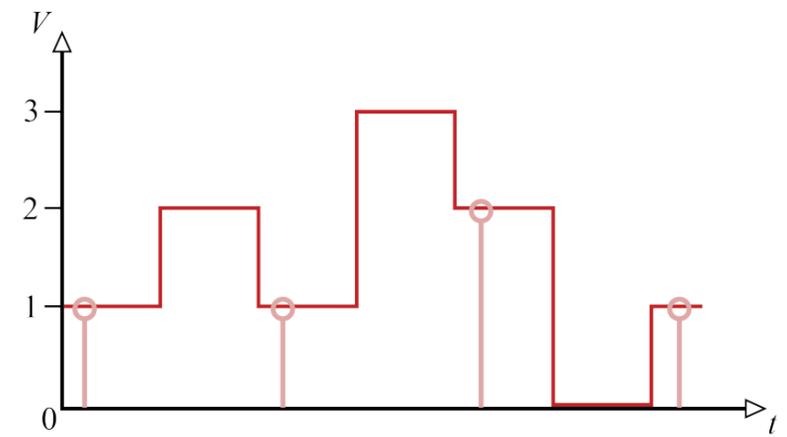


# Distinguishing Pixels

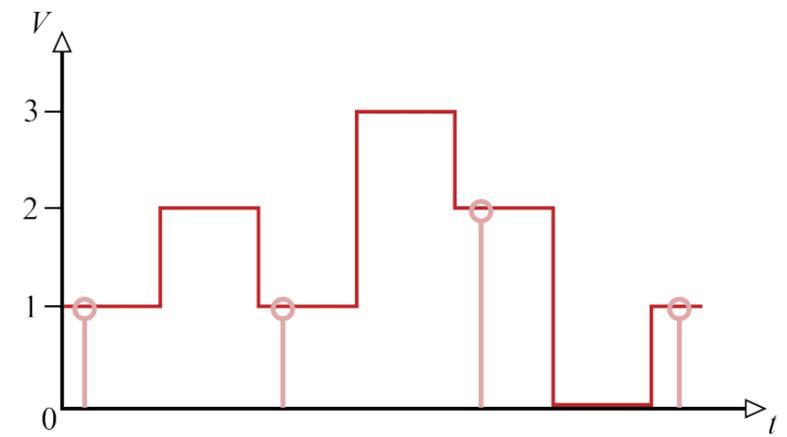
# Distinguishing Pixels



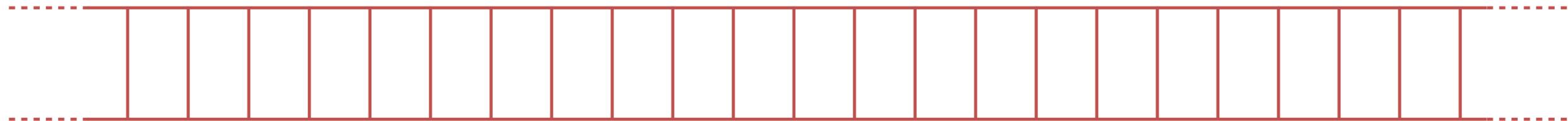
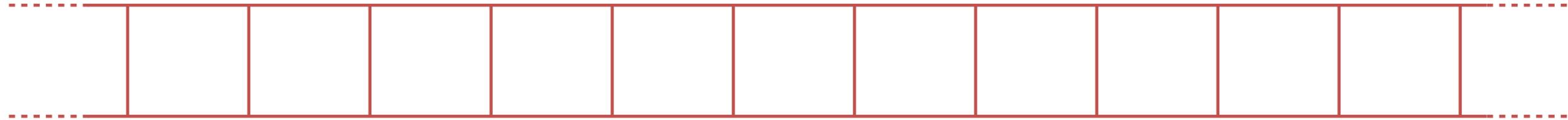
# Distinguishing Pixels



# Distinguishing Pixels

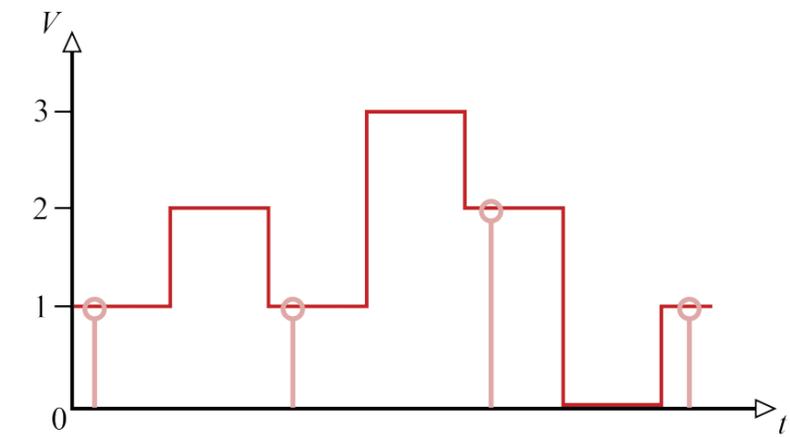


*Input Signal*

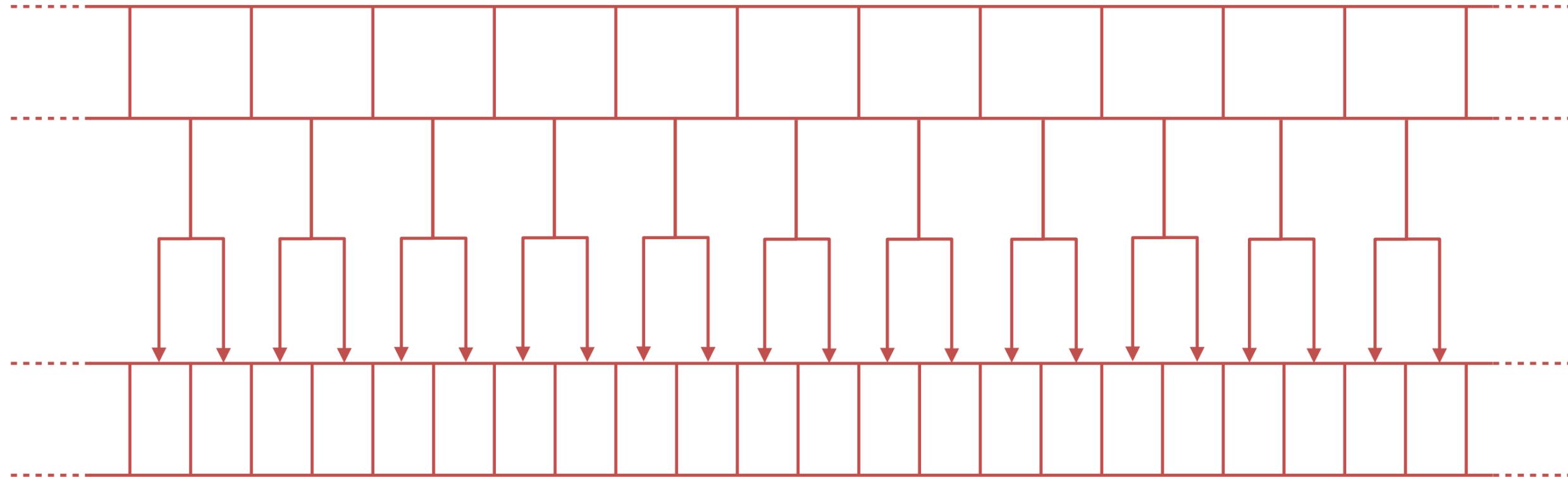


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

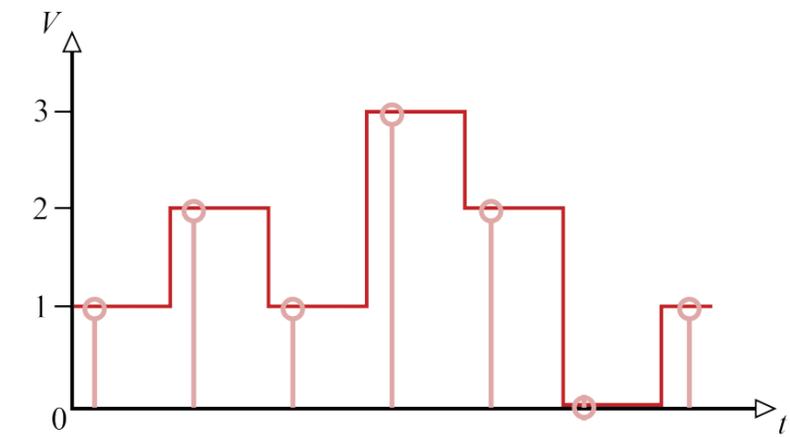


*Input Signal*

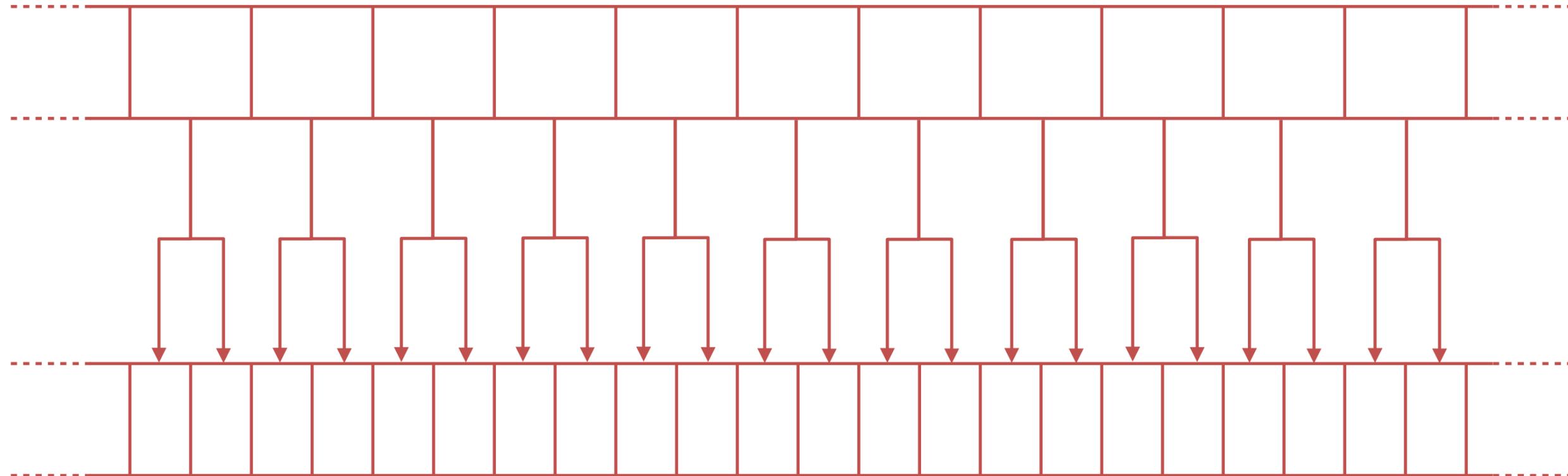


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

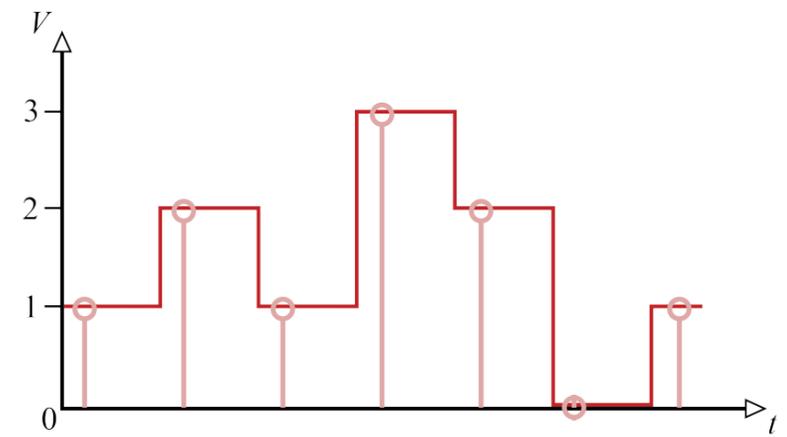


*Input Signal*

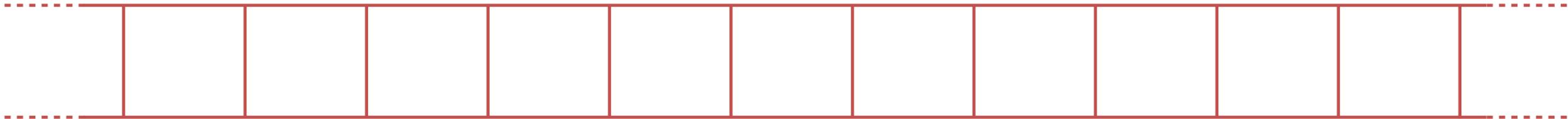
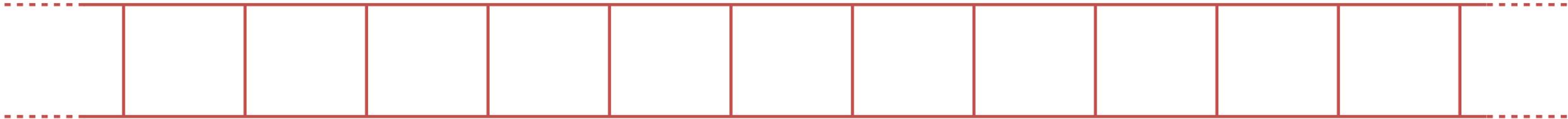


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

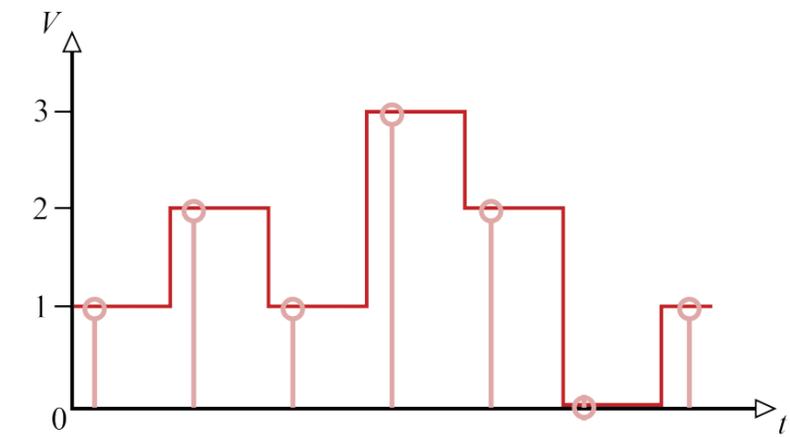


*Input Signal*

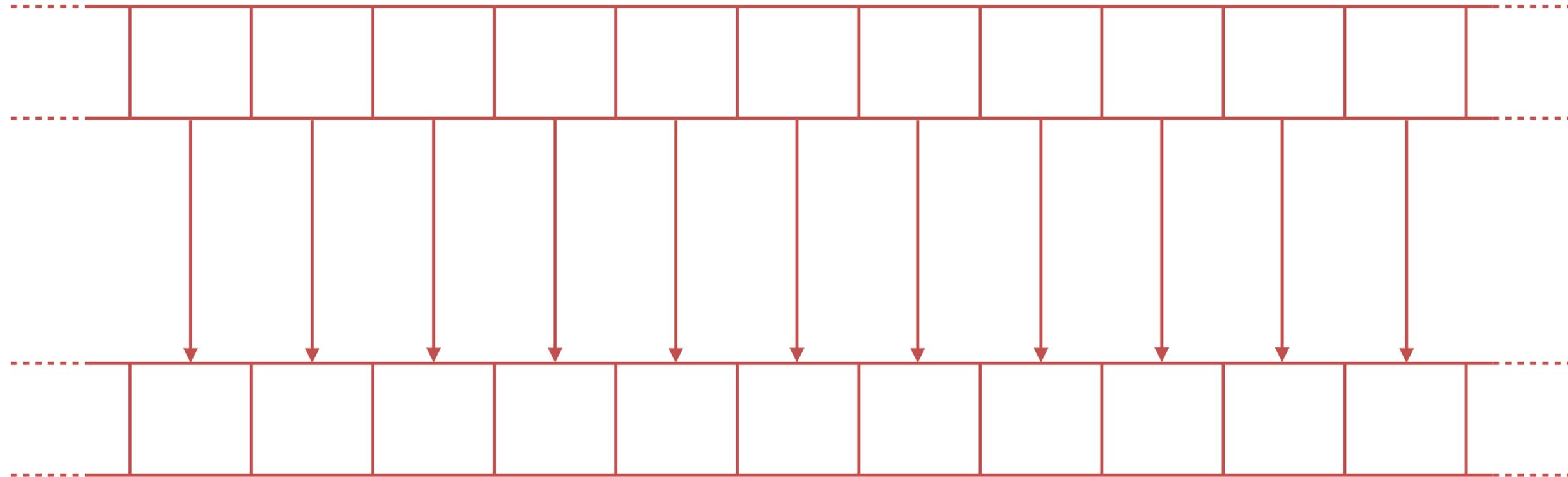


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

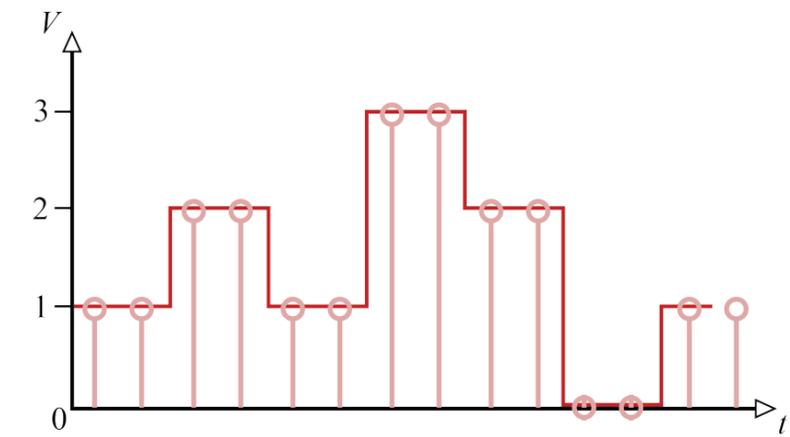


*Input Signal*

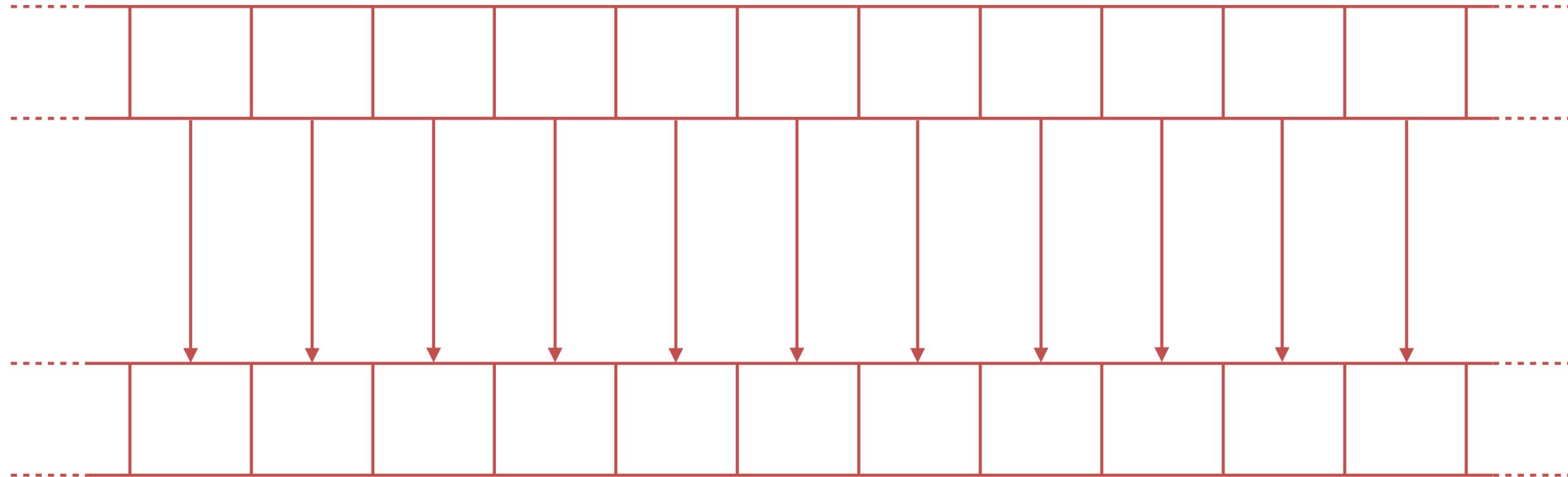


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

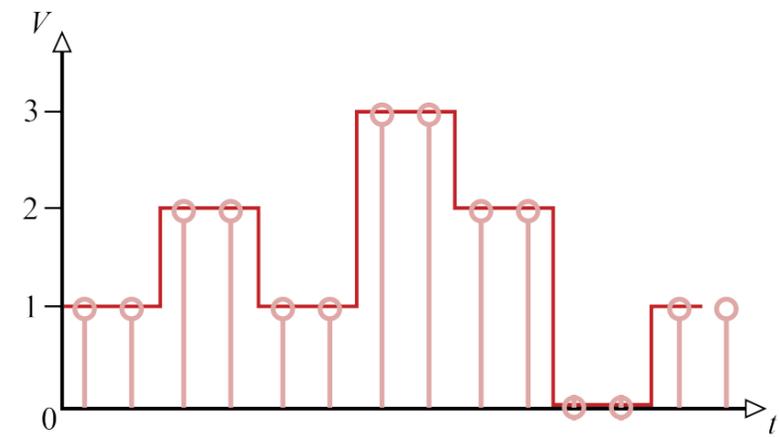


*Input Signal*

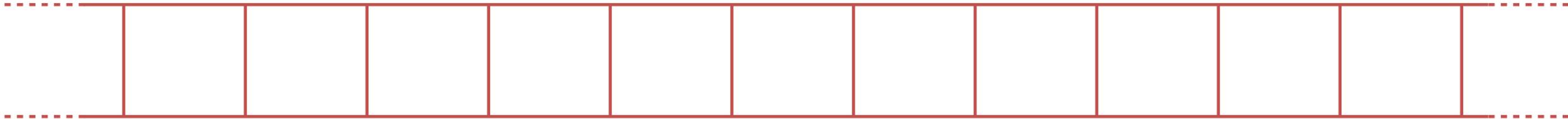


*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

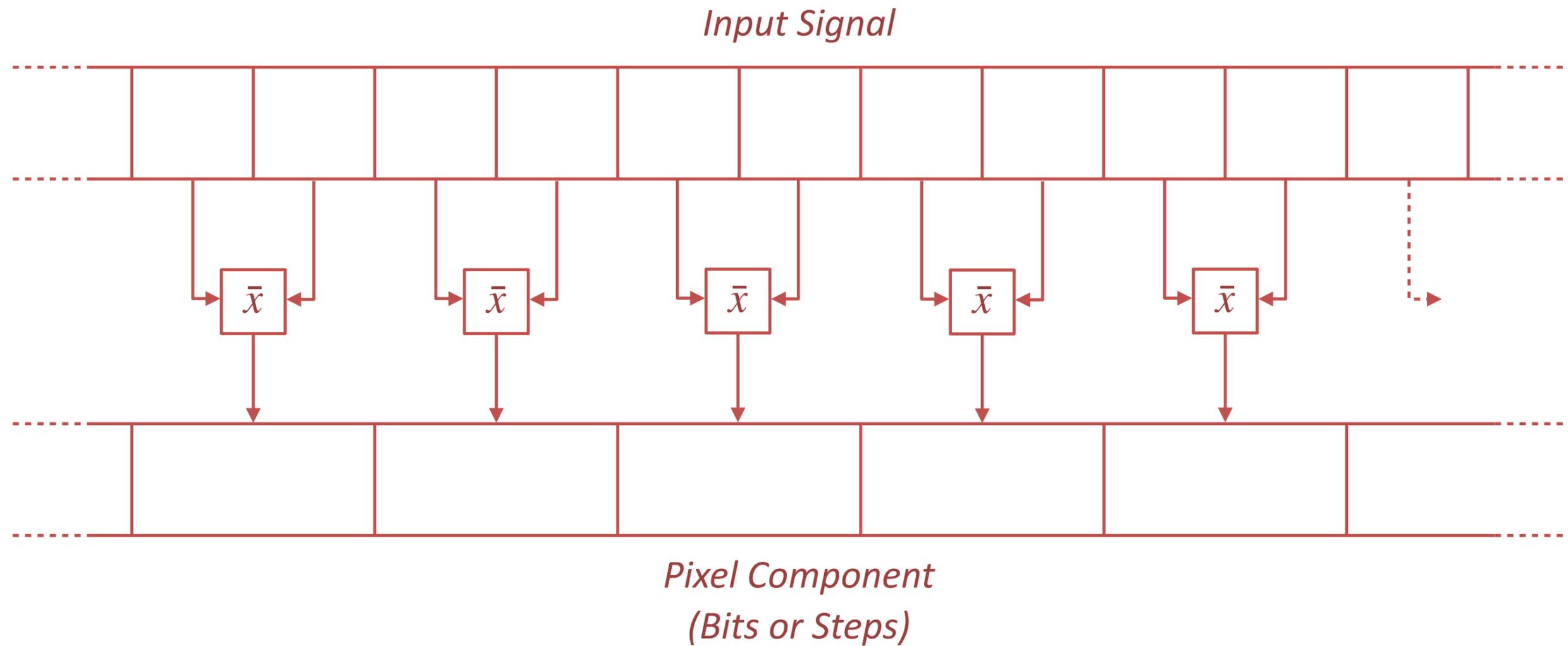
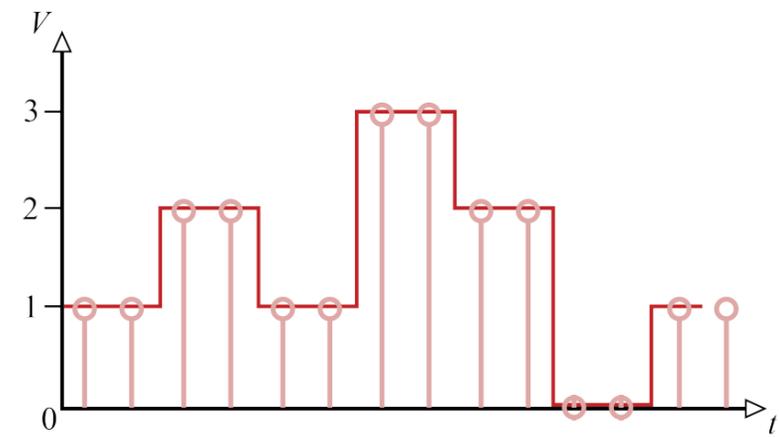


*Input Signal*



*Pixel Component  
(Bits or Steps)*

# Distinguishing Pixels

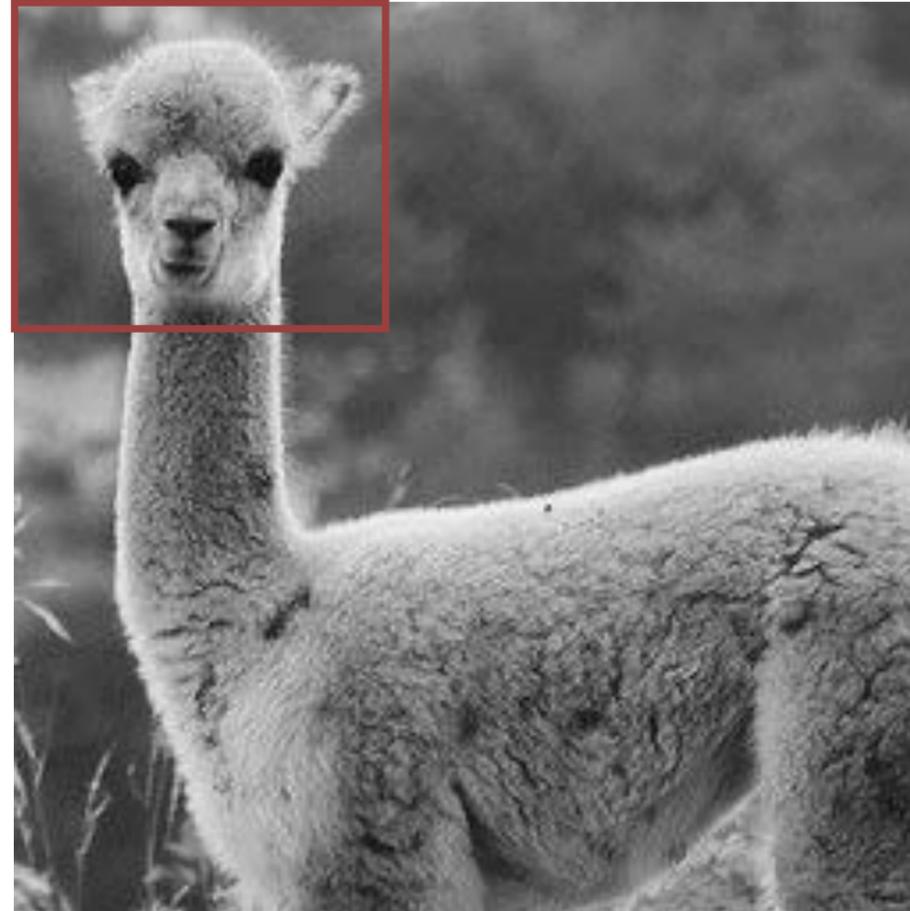


# Distinguishing Frames

# Distinguishing Frames



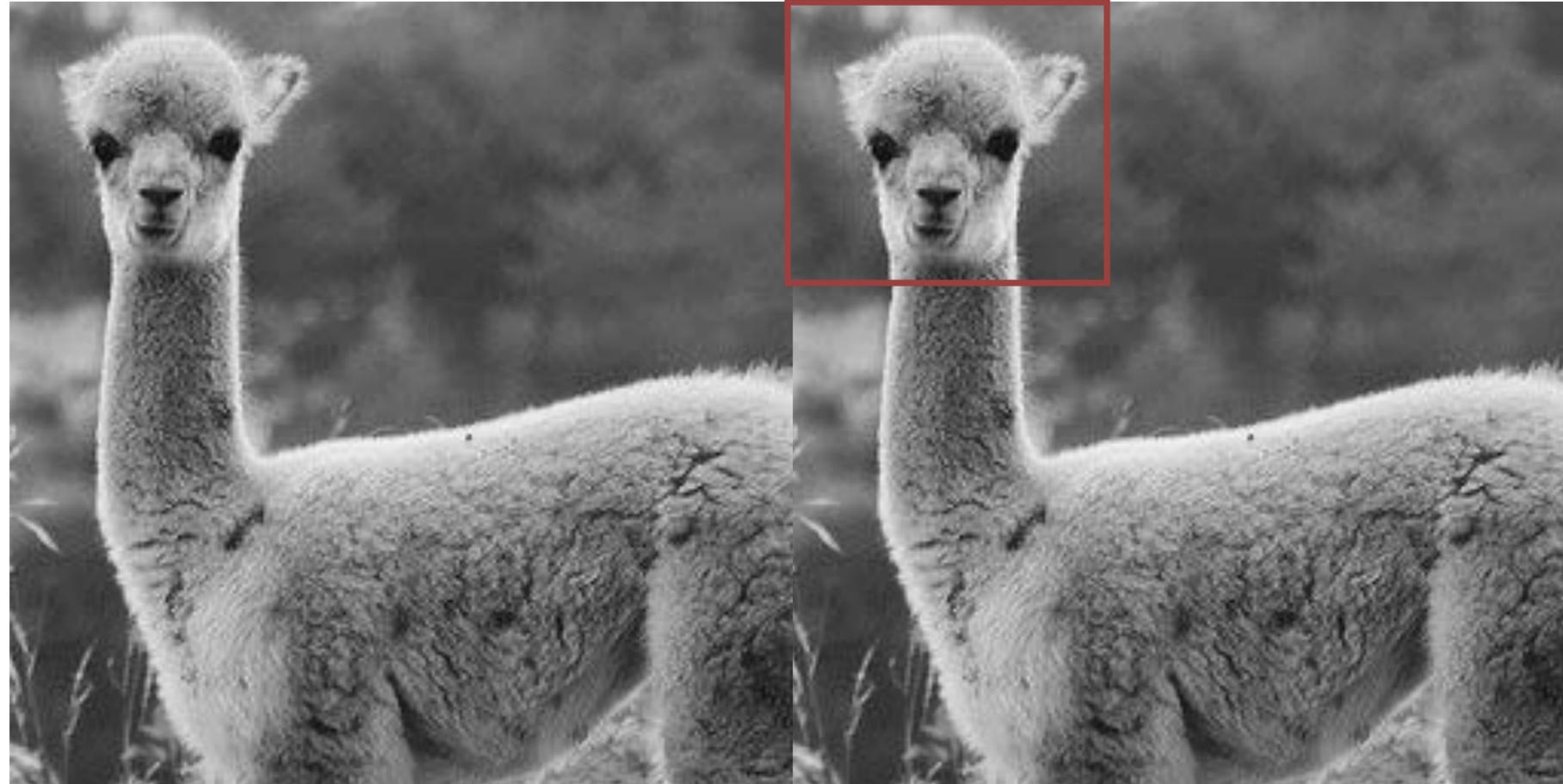
# Distinguishing Frames



# Distinguishing Frames



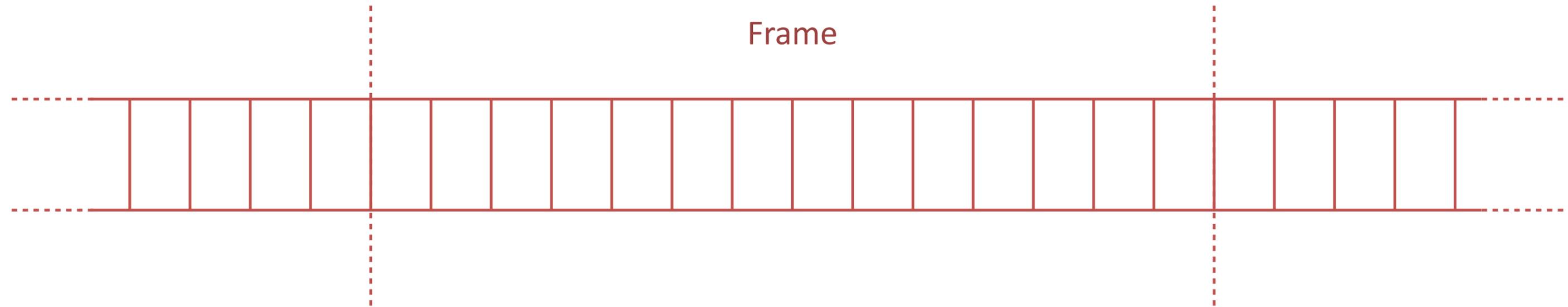
# Distinguishing Frames



# Alignment

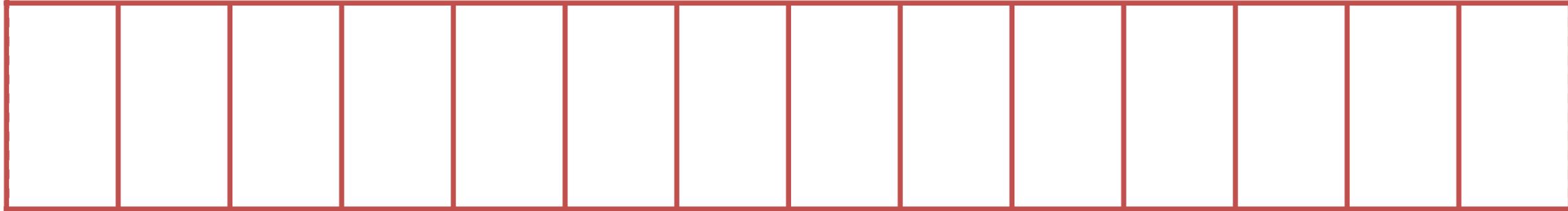


# Alignment

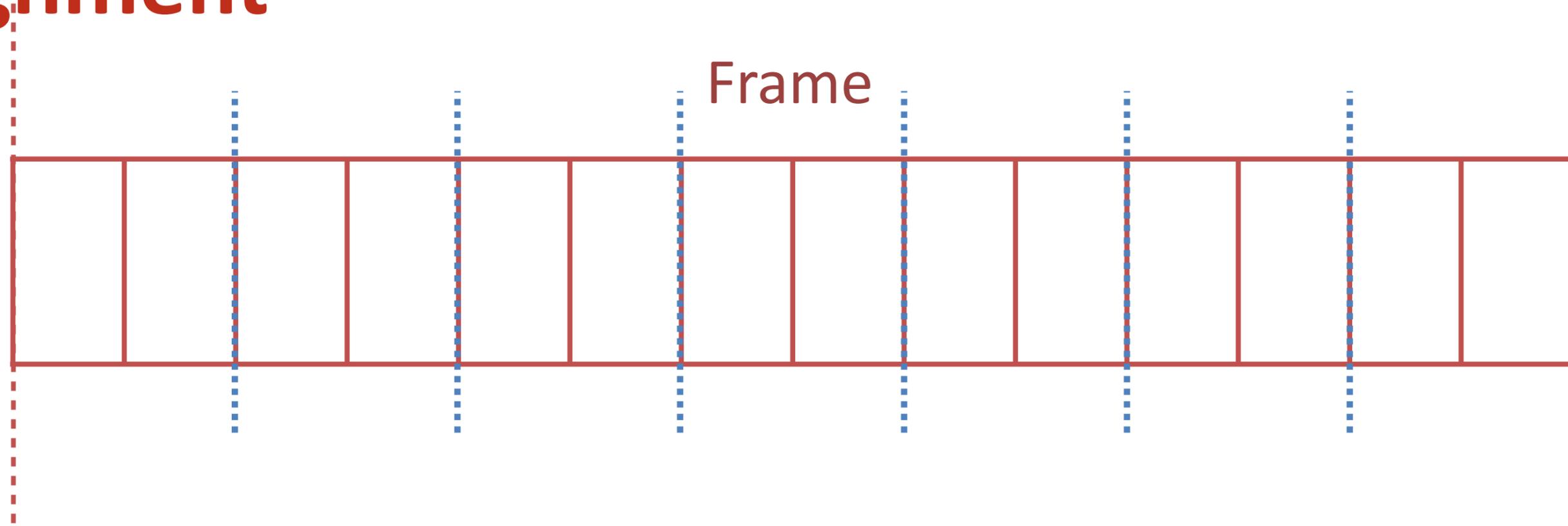


# Alignment

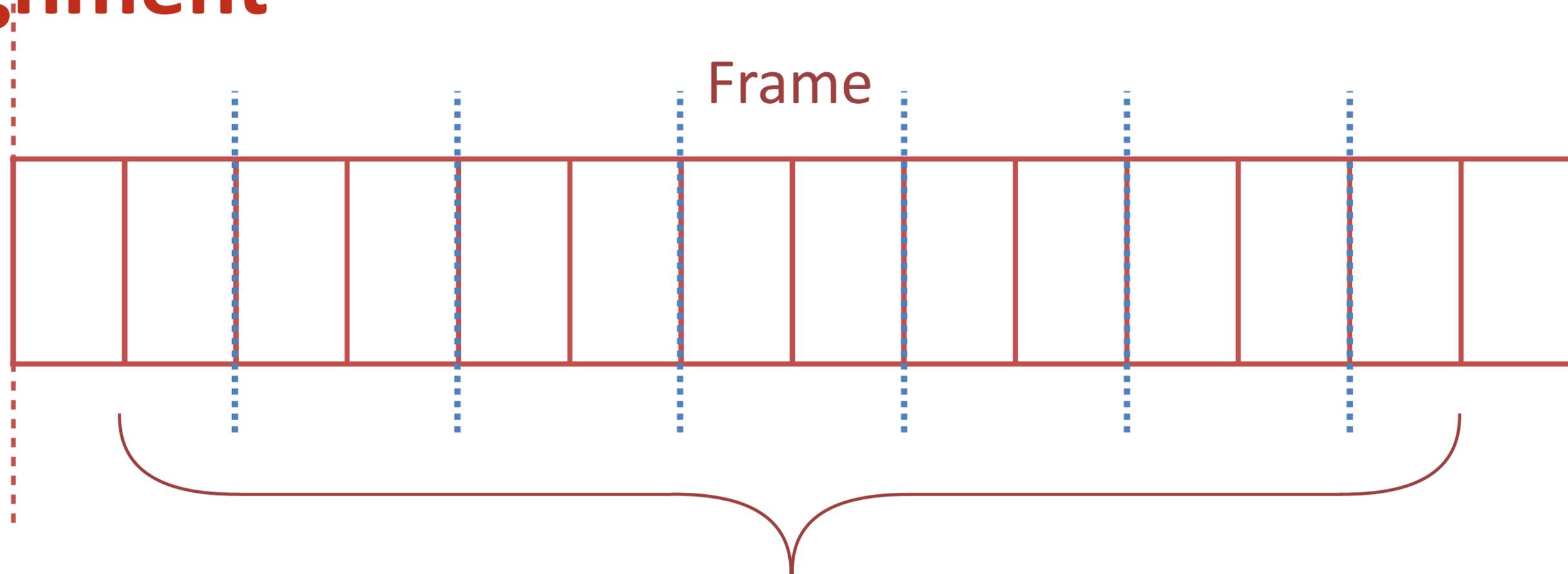
Frame



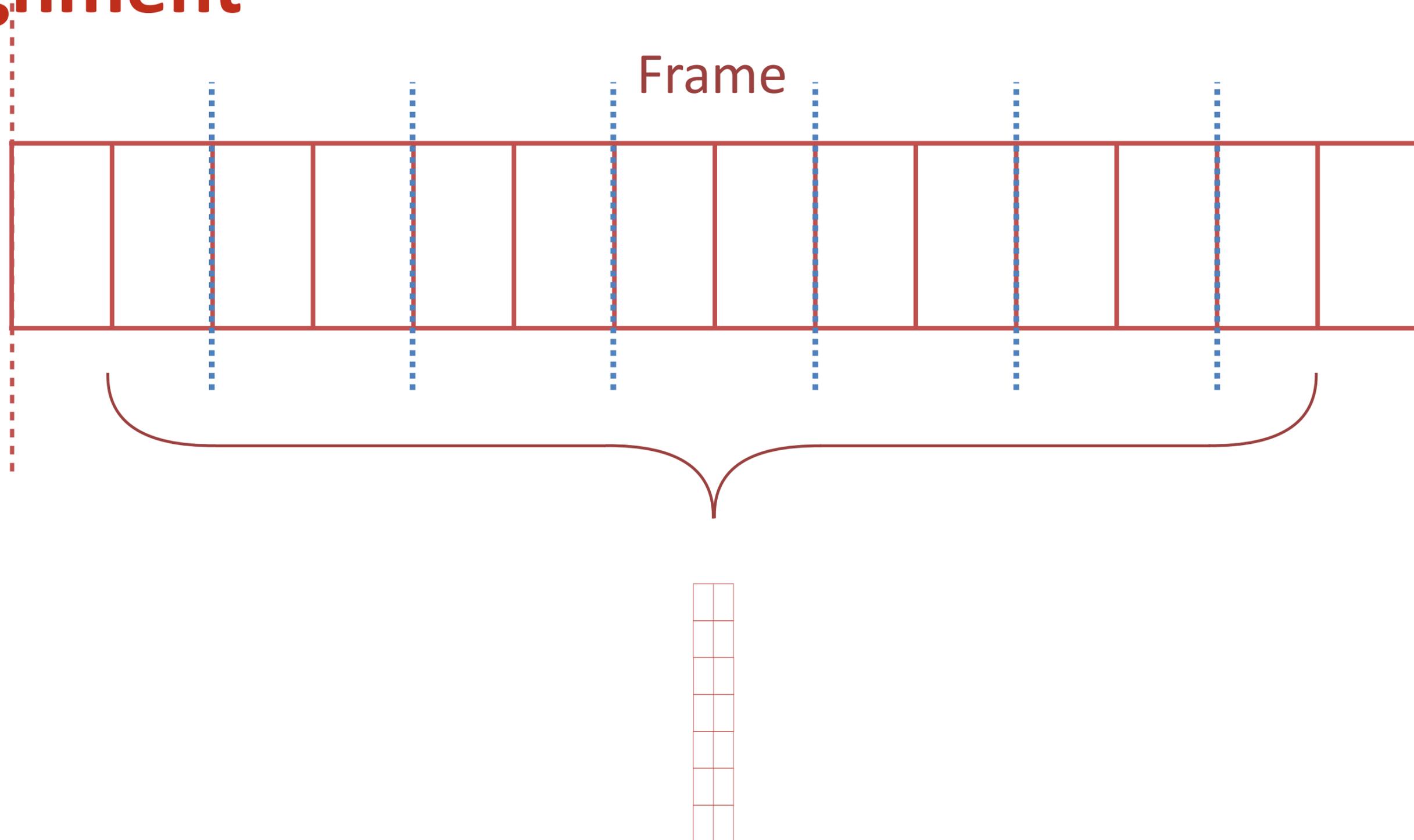
# Alignment



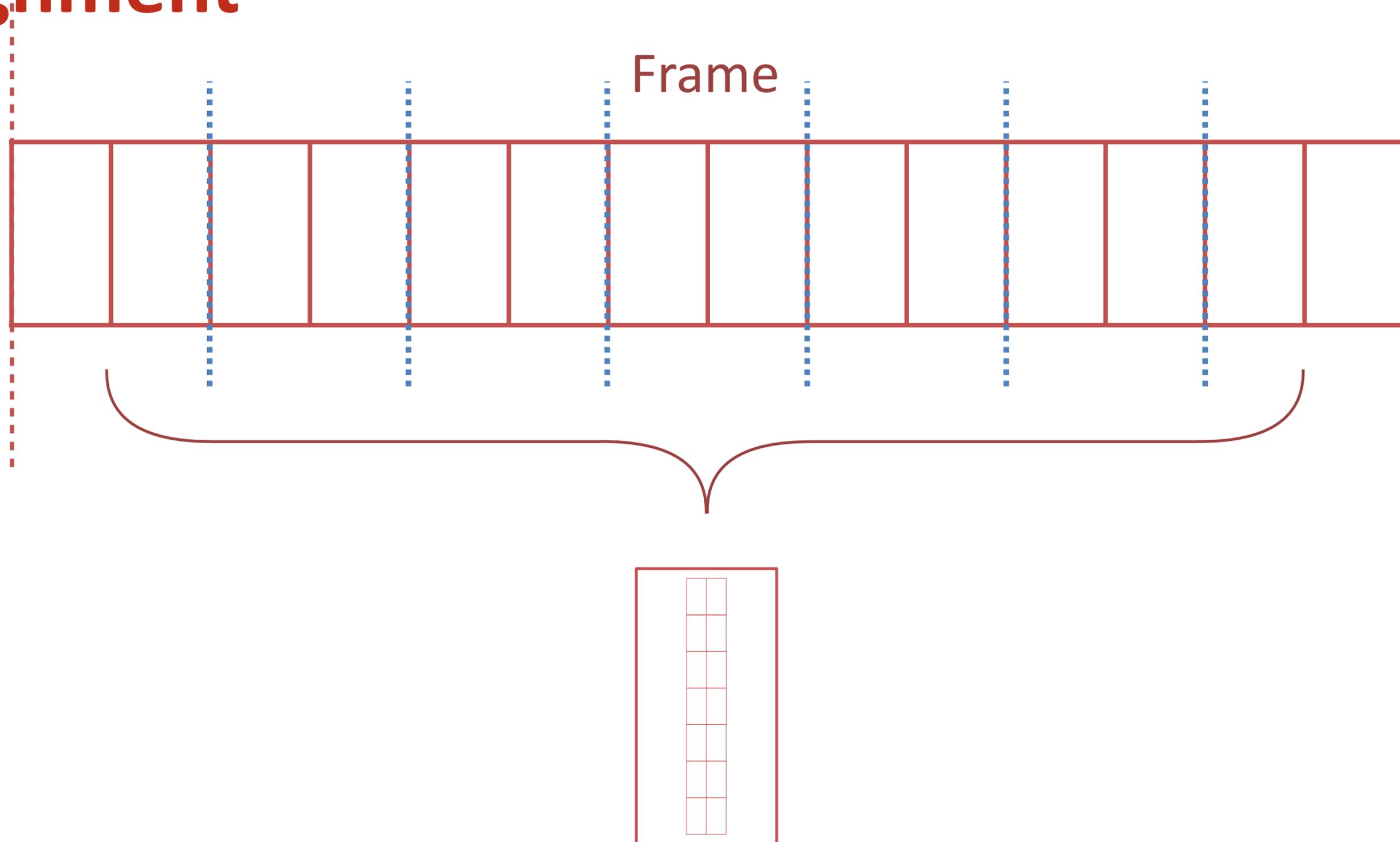
# Alignment



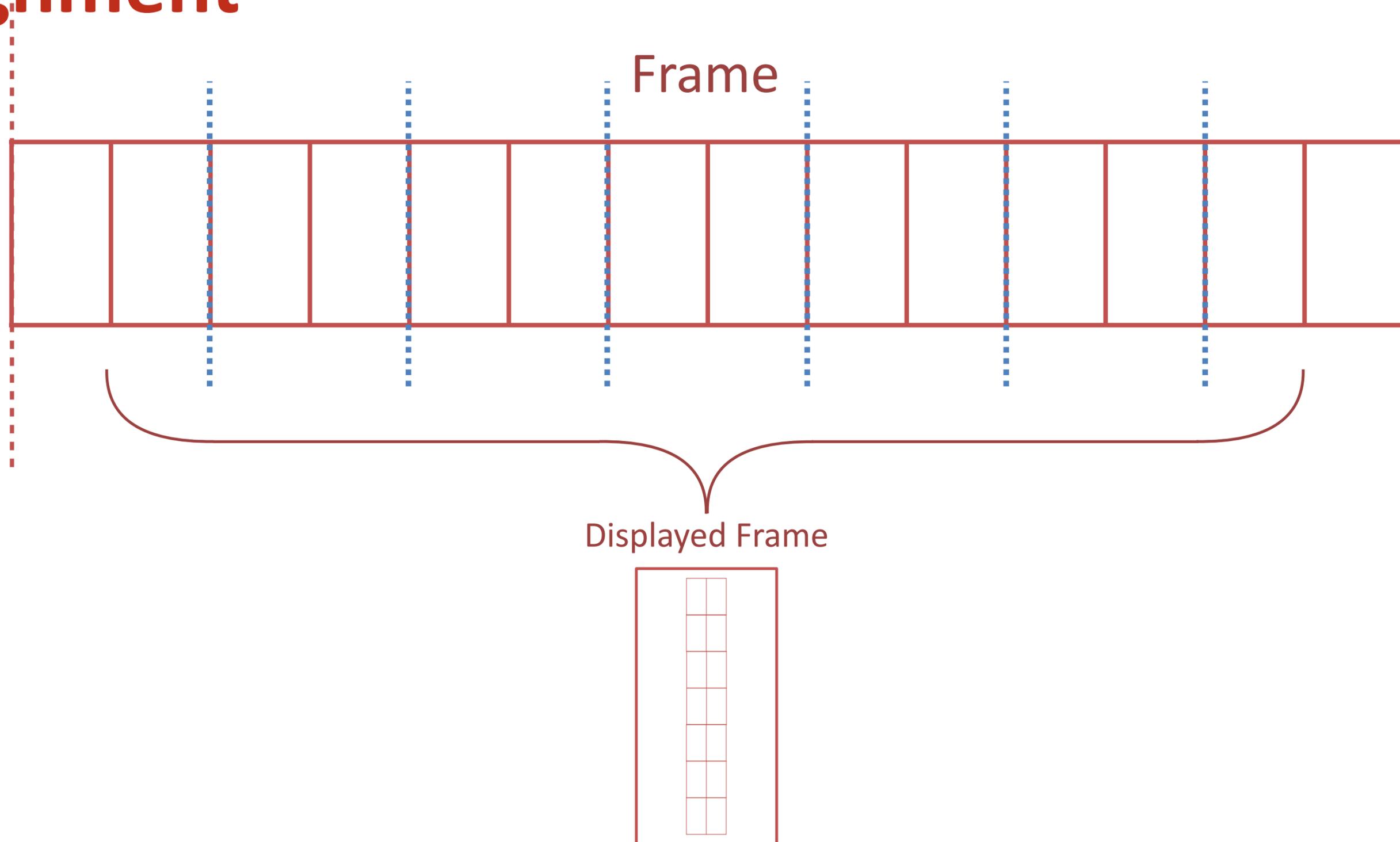
# Alignment



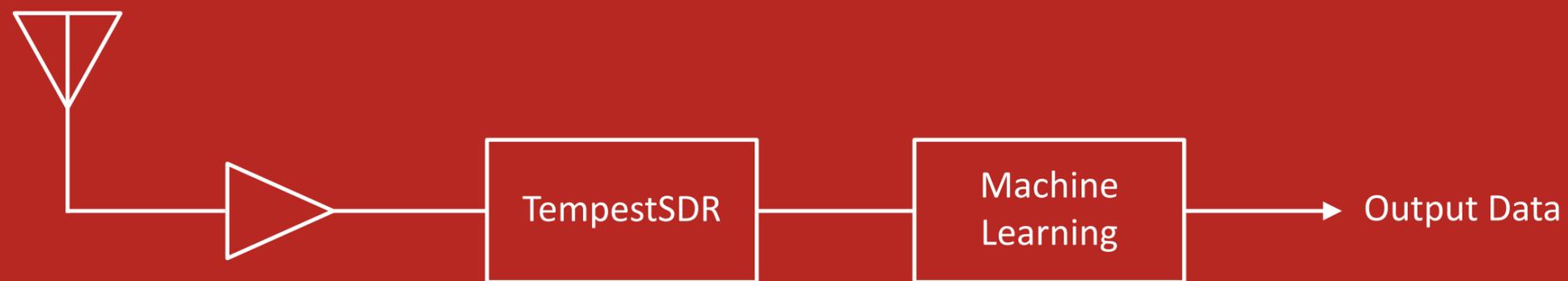
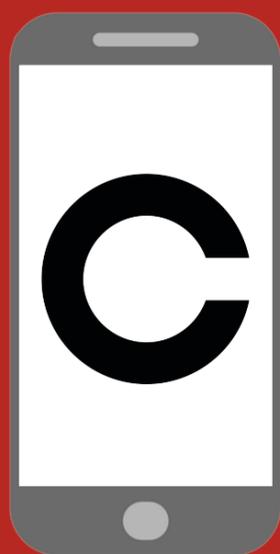
# Alignment



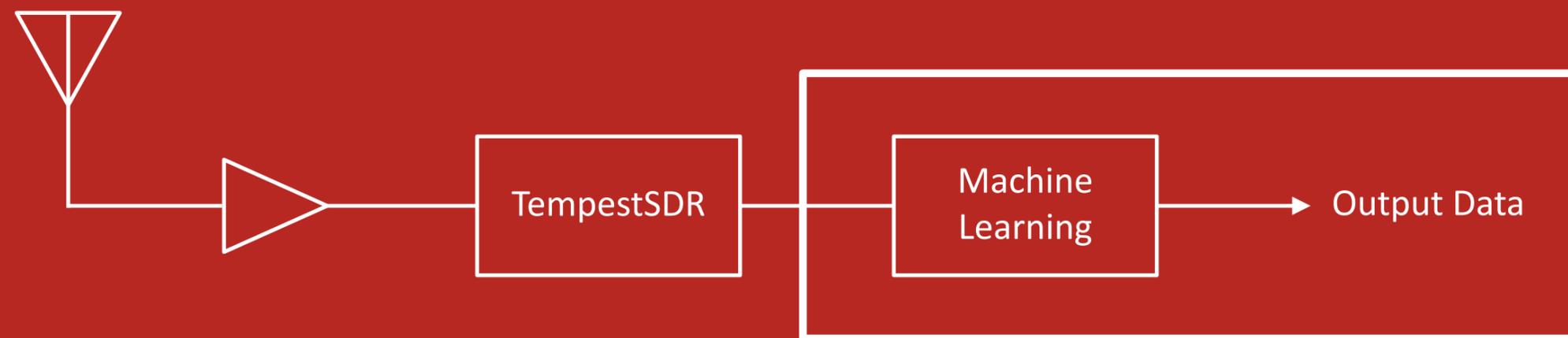
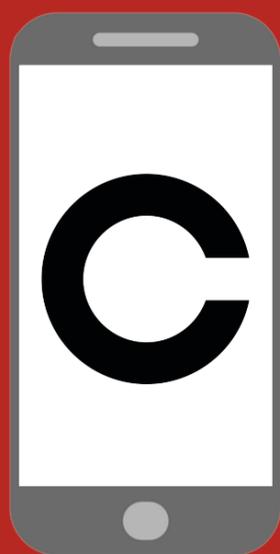
# Alignment



# Machine Learning

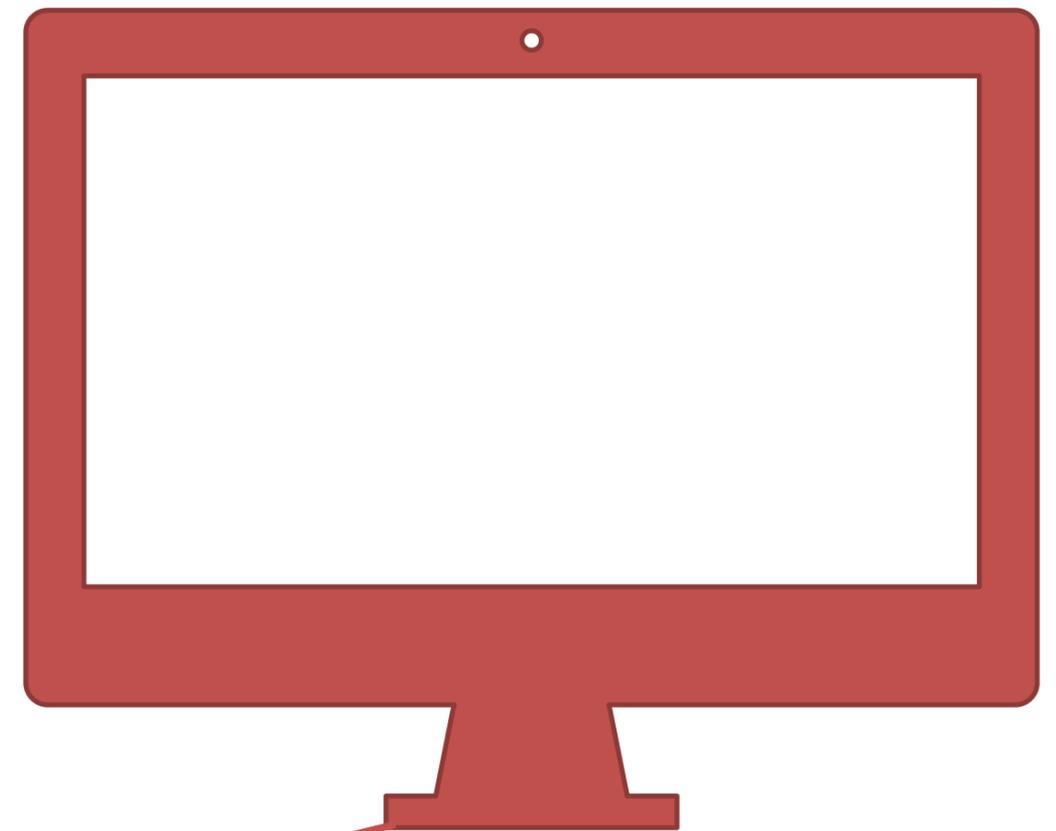
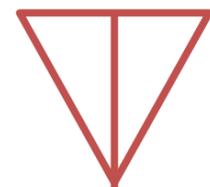
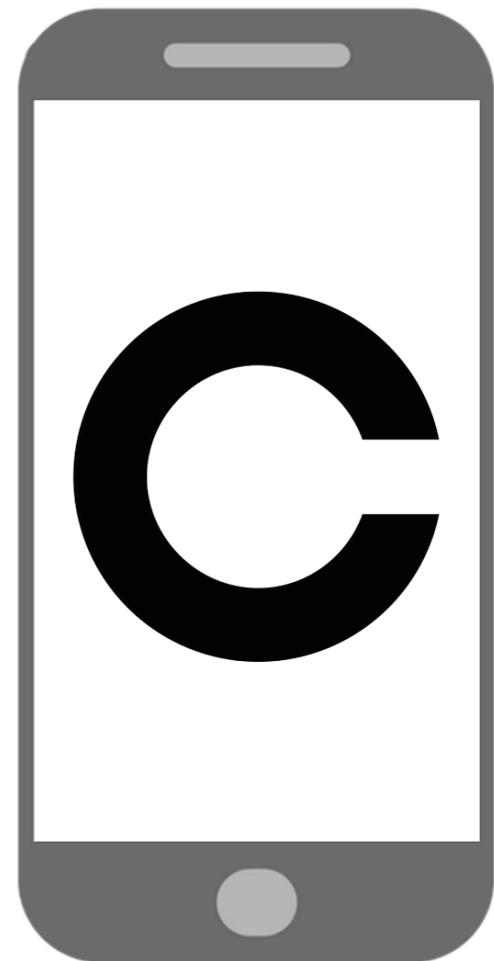


# Machine Learning

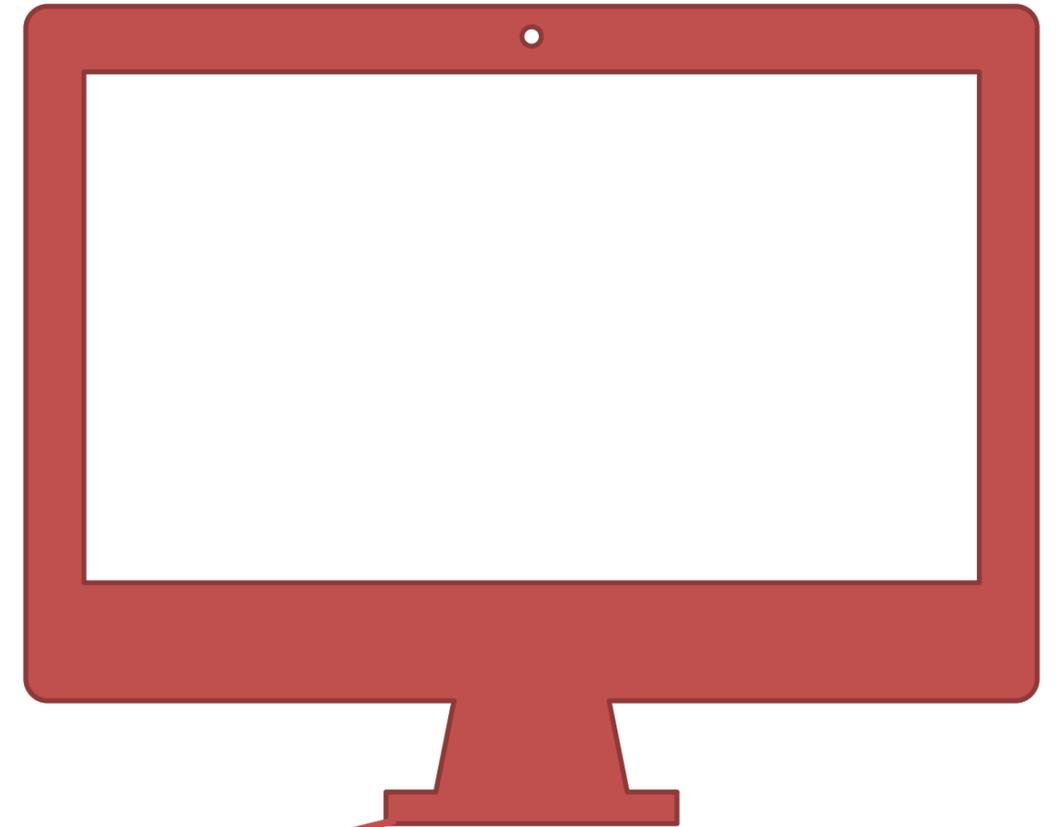
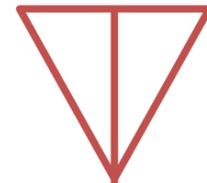


# Use Cases

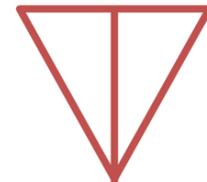
# Use Cases



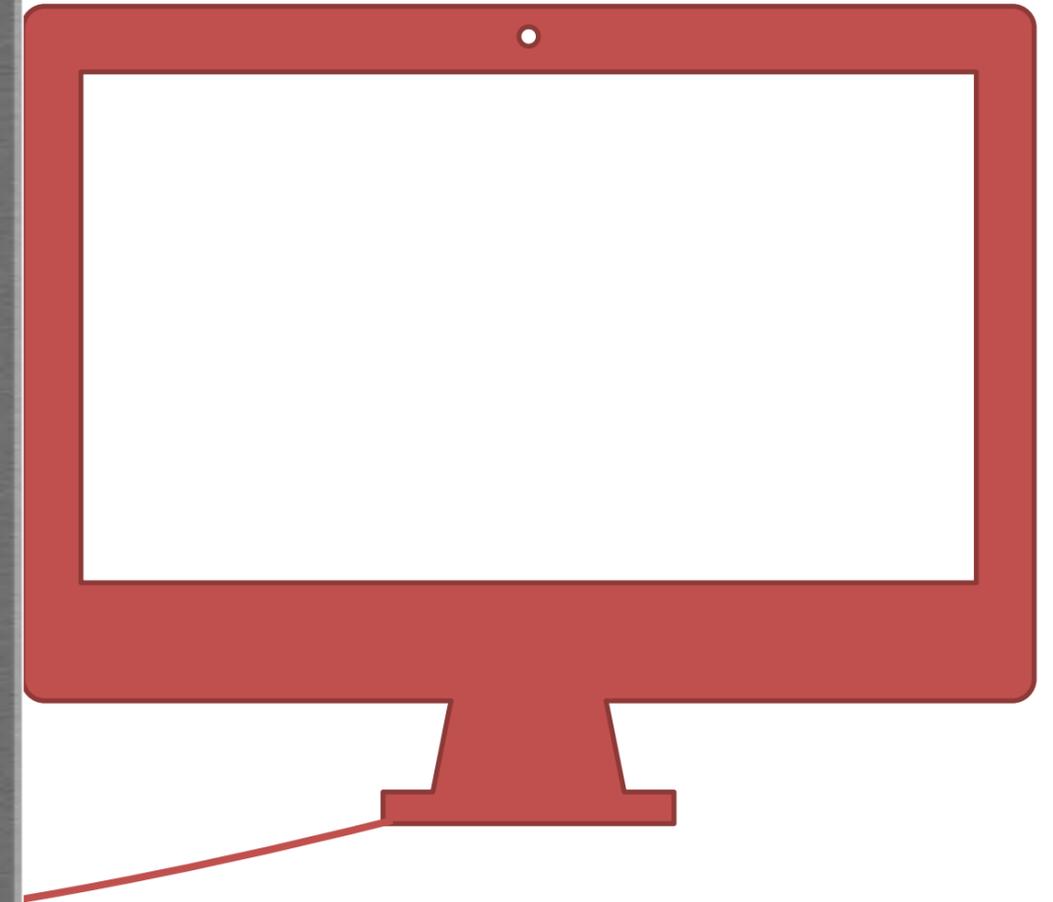
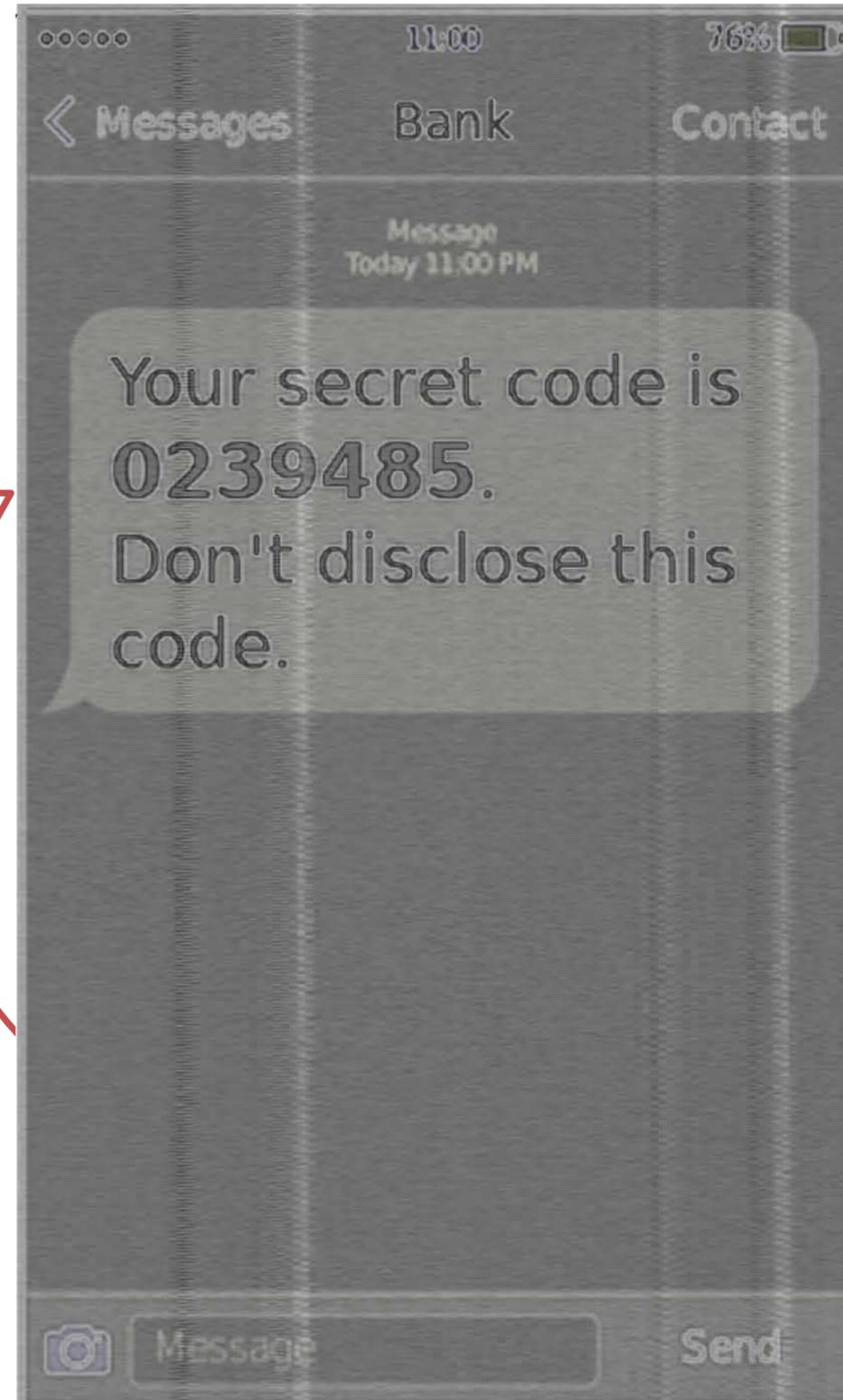
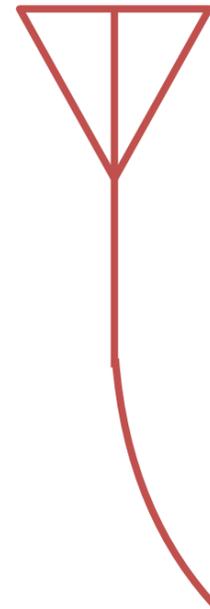
# Use Cases



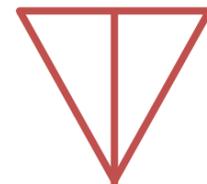
# Use Cases



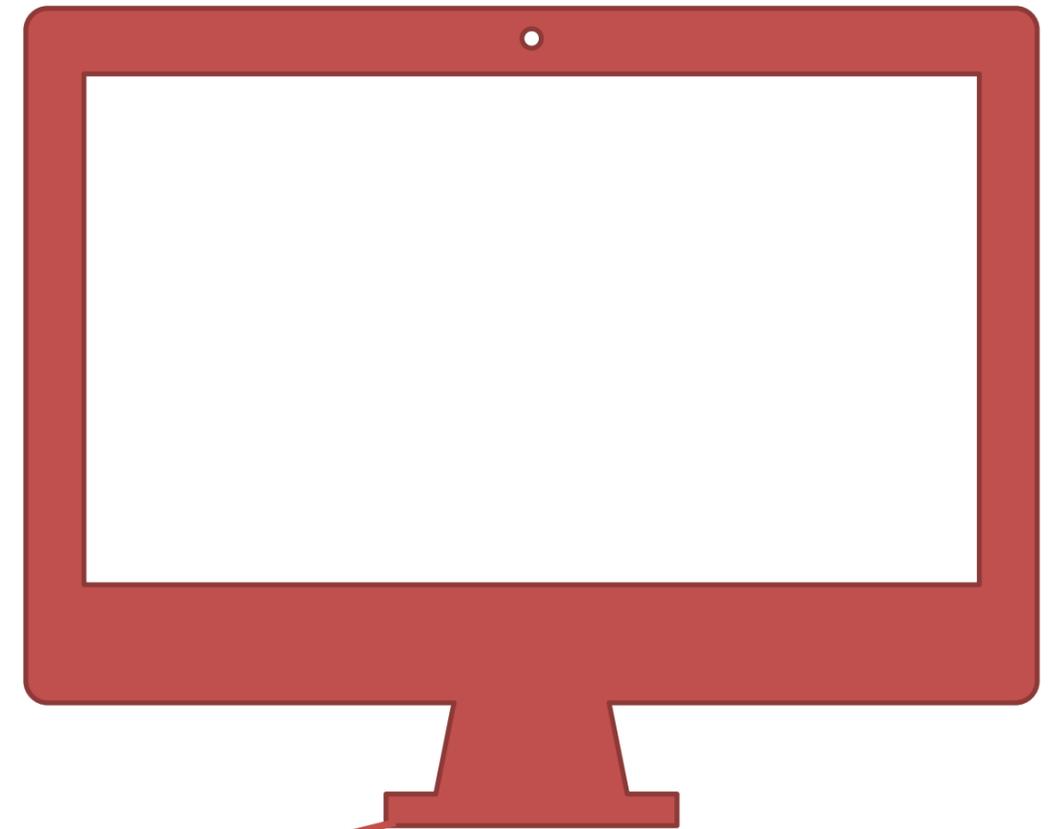
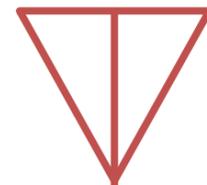
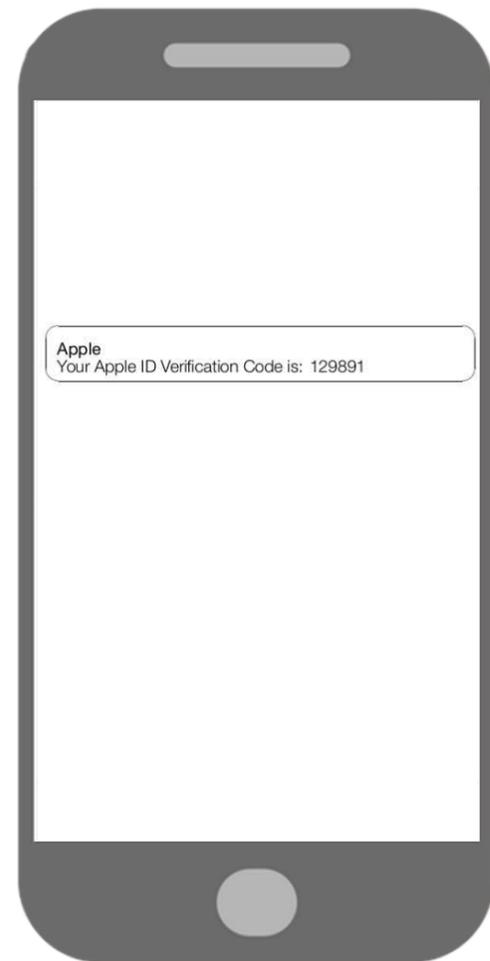
# Use Cases



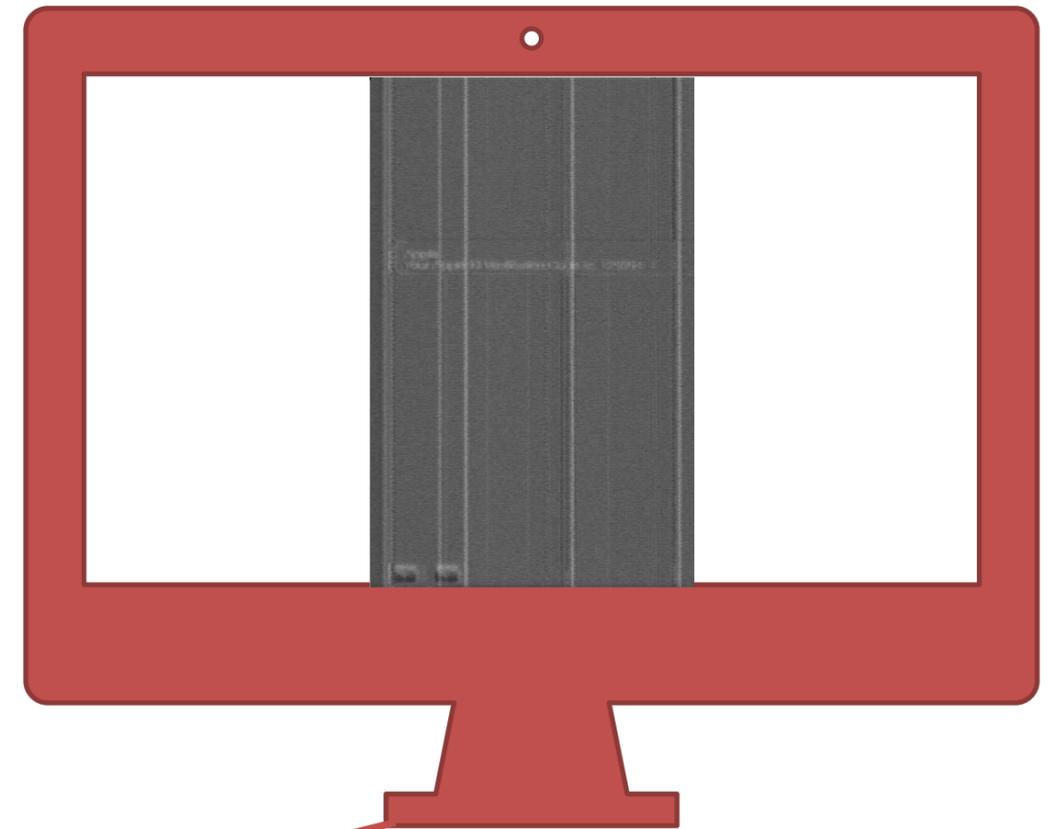
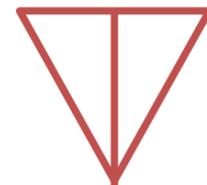
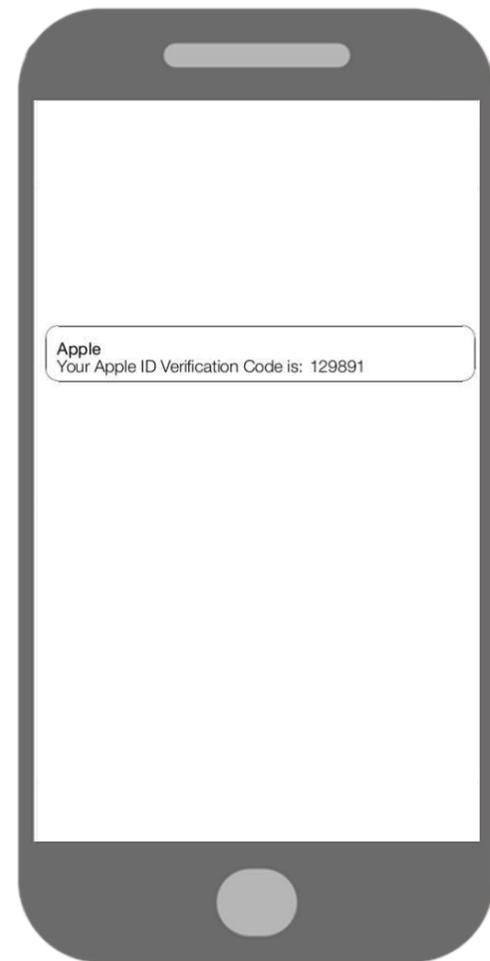
# Use Cases



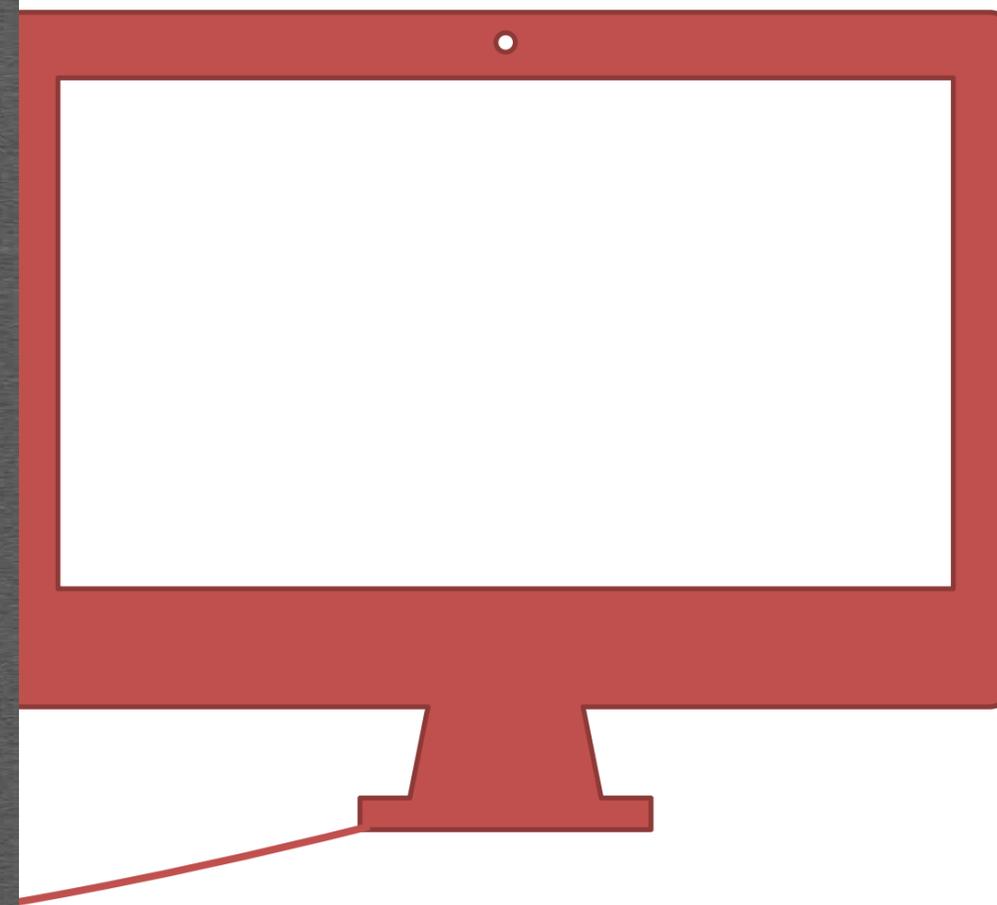
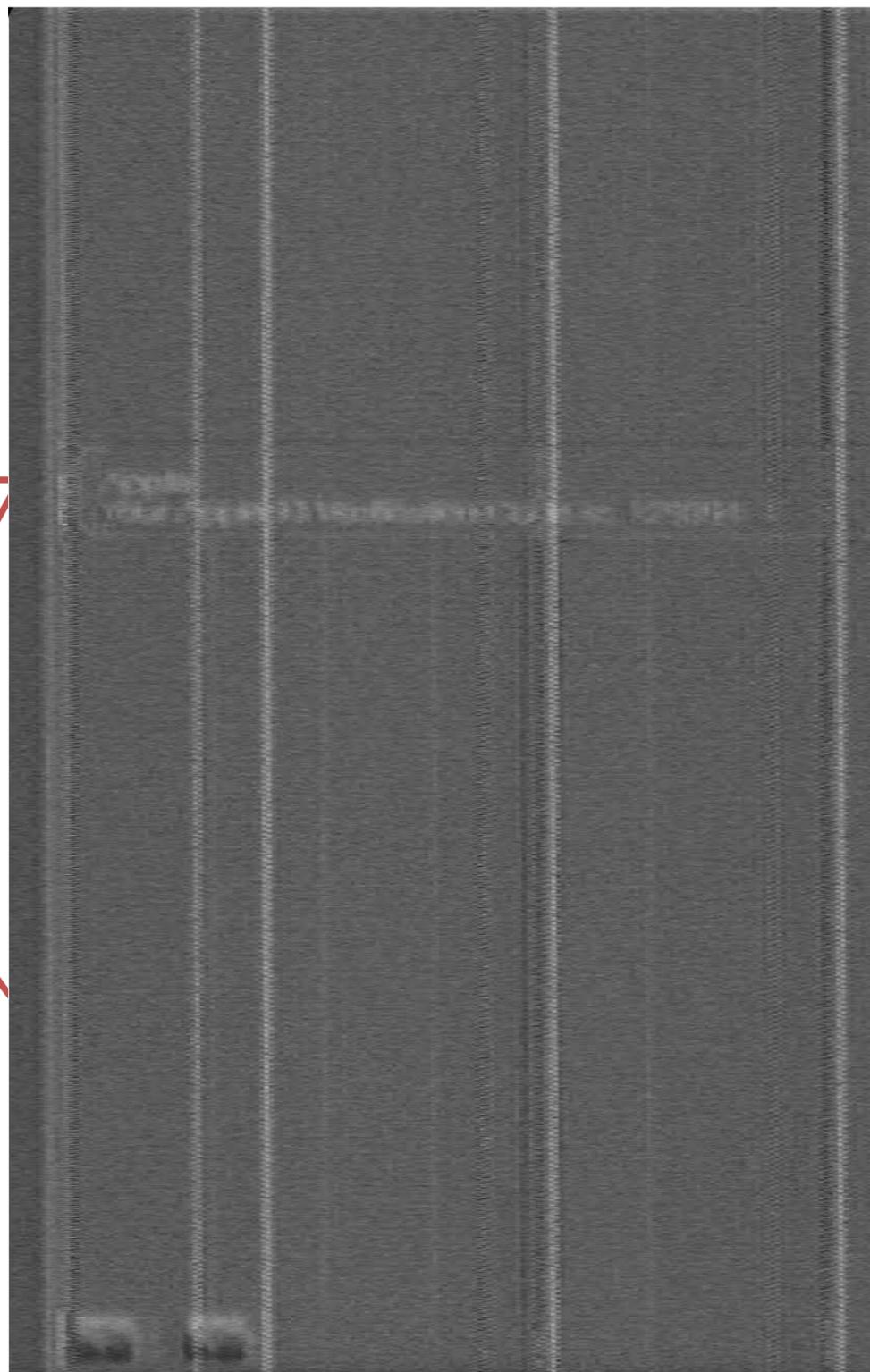
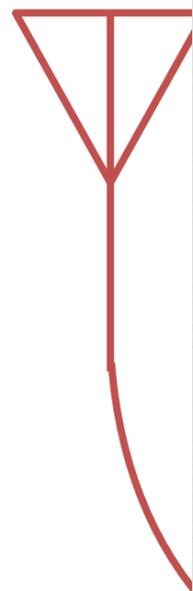
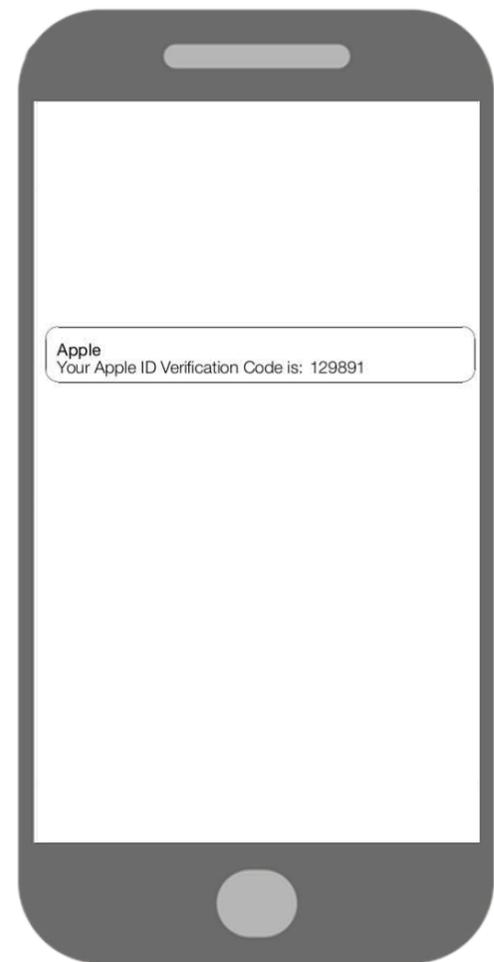
# Use Cases



# Use Cases



# Use Cases

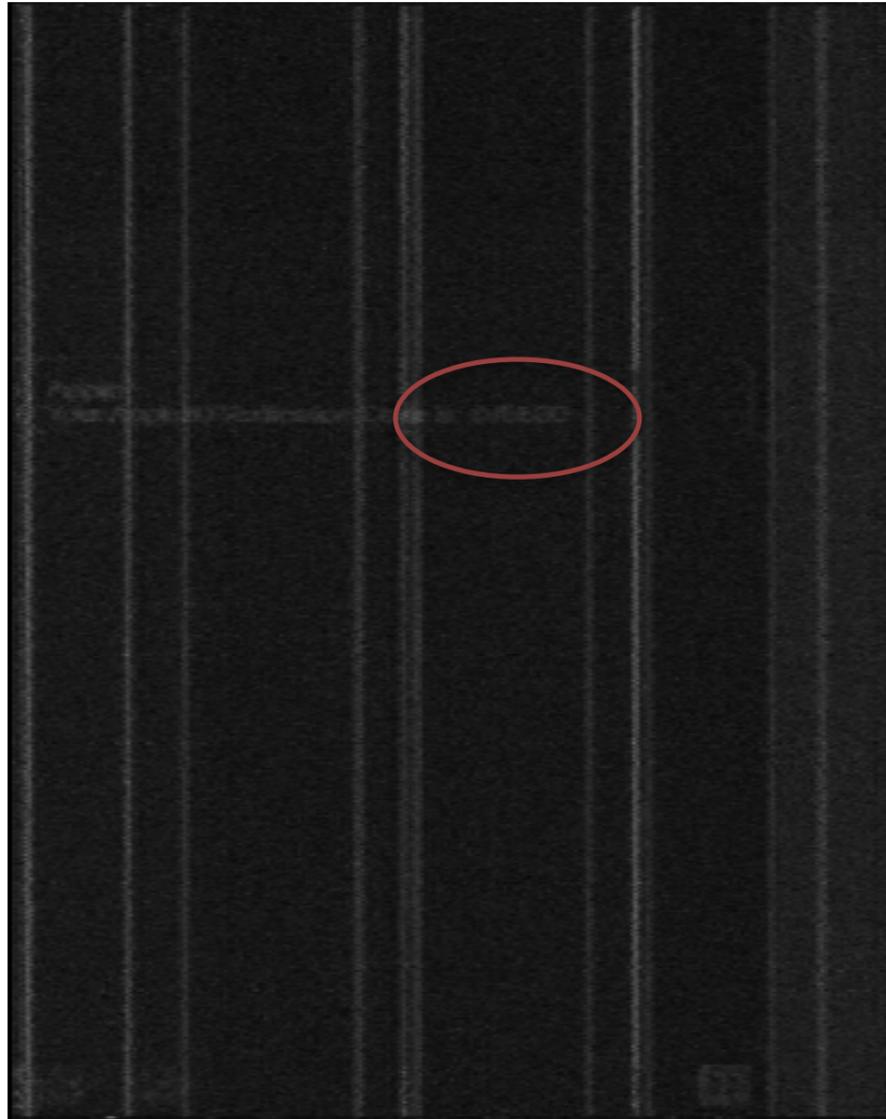


# Finding the Security Code

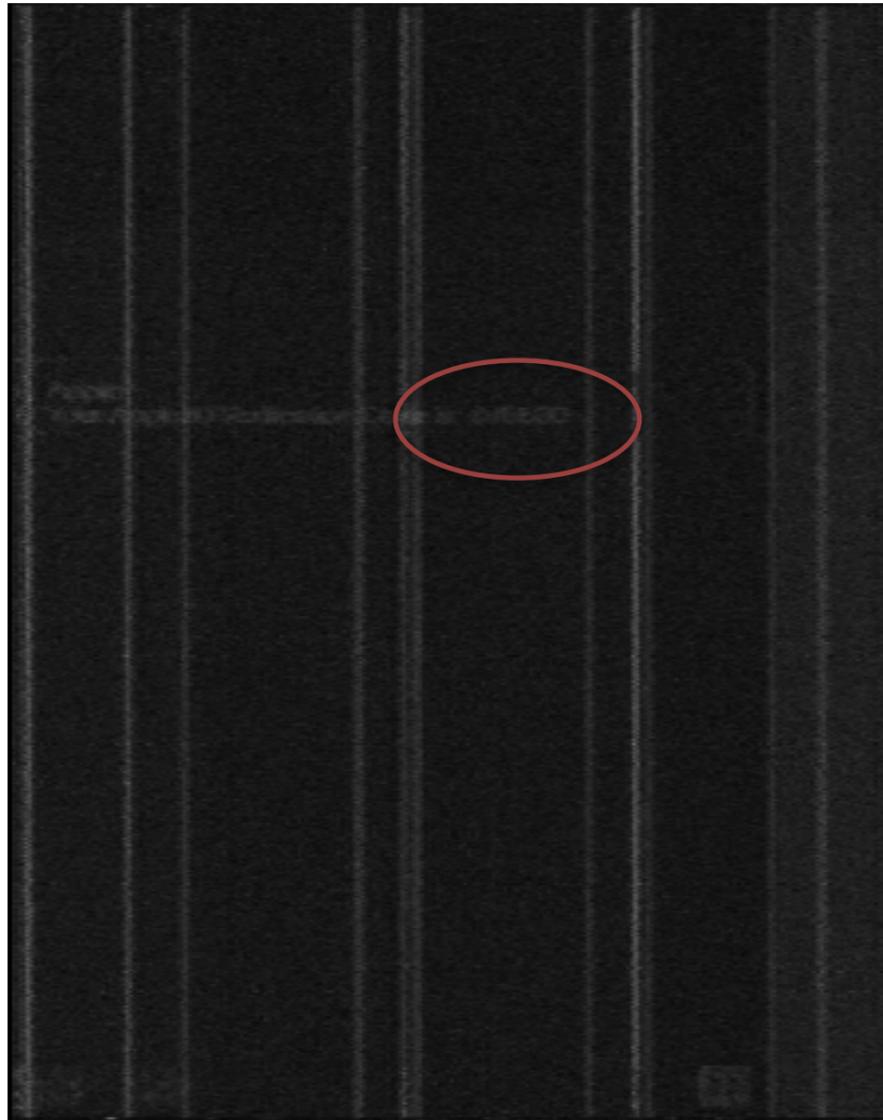
# Finding the Security Code



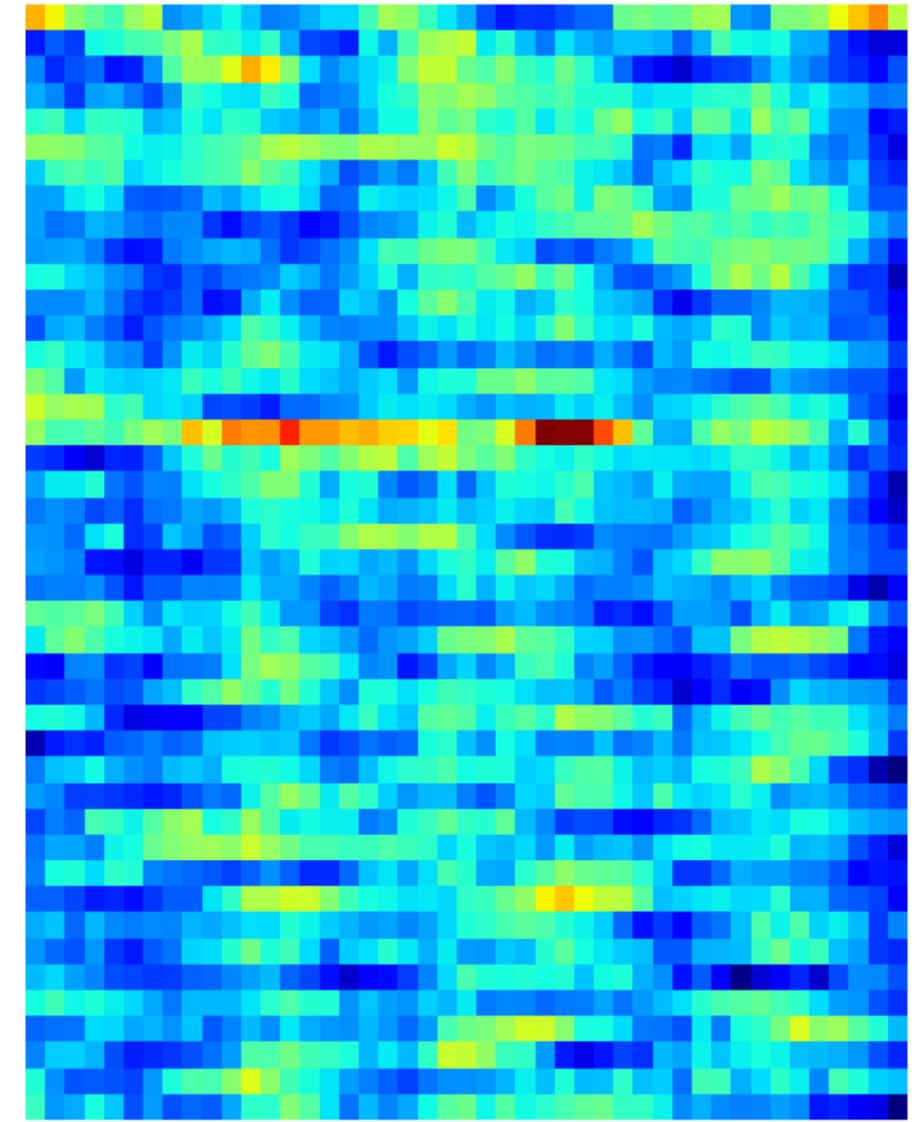
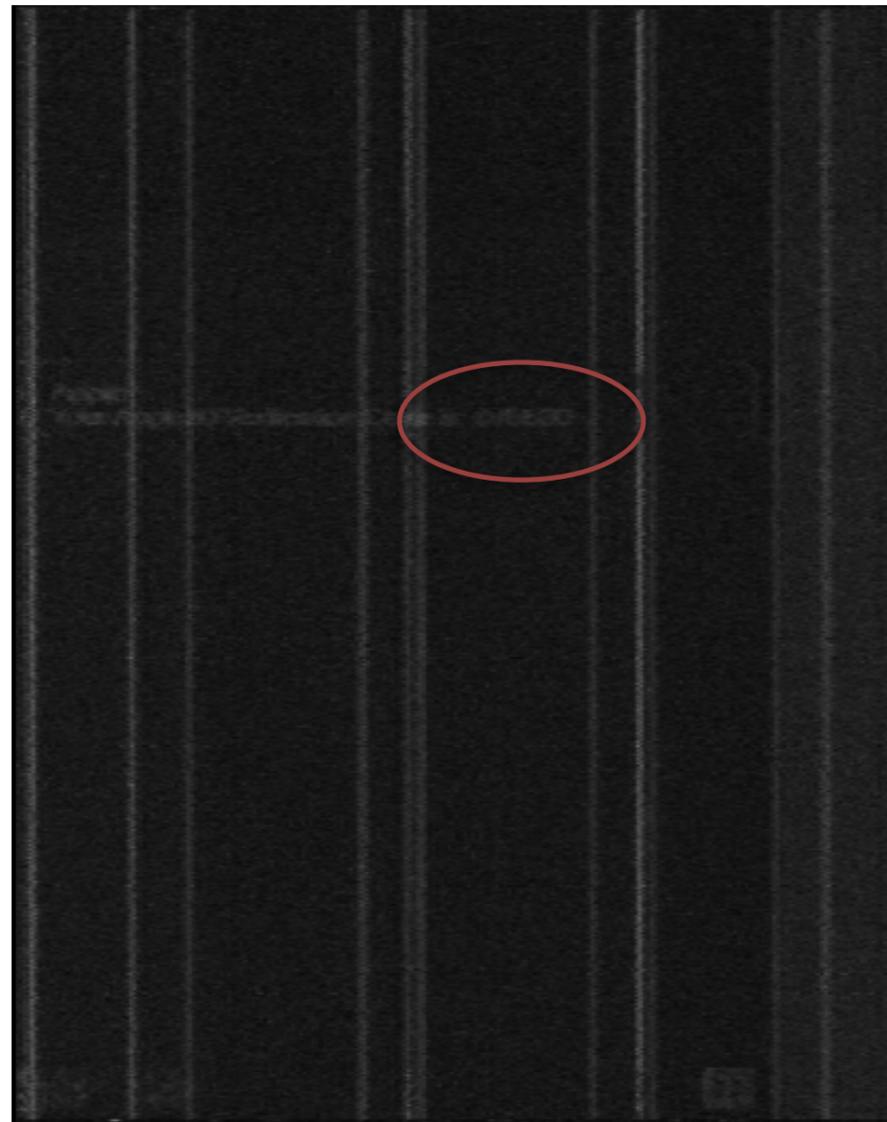
# Finding the Security Code



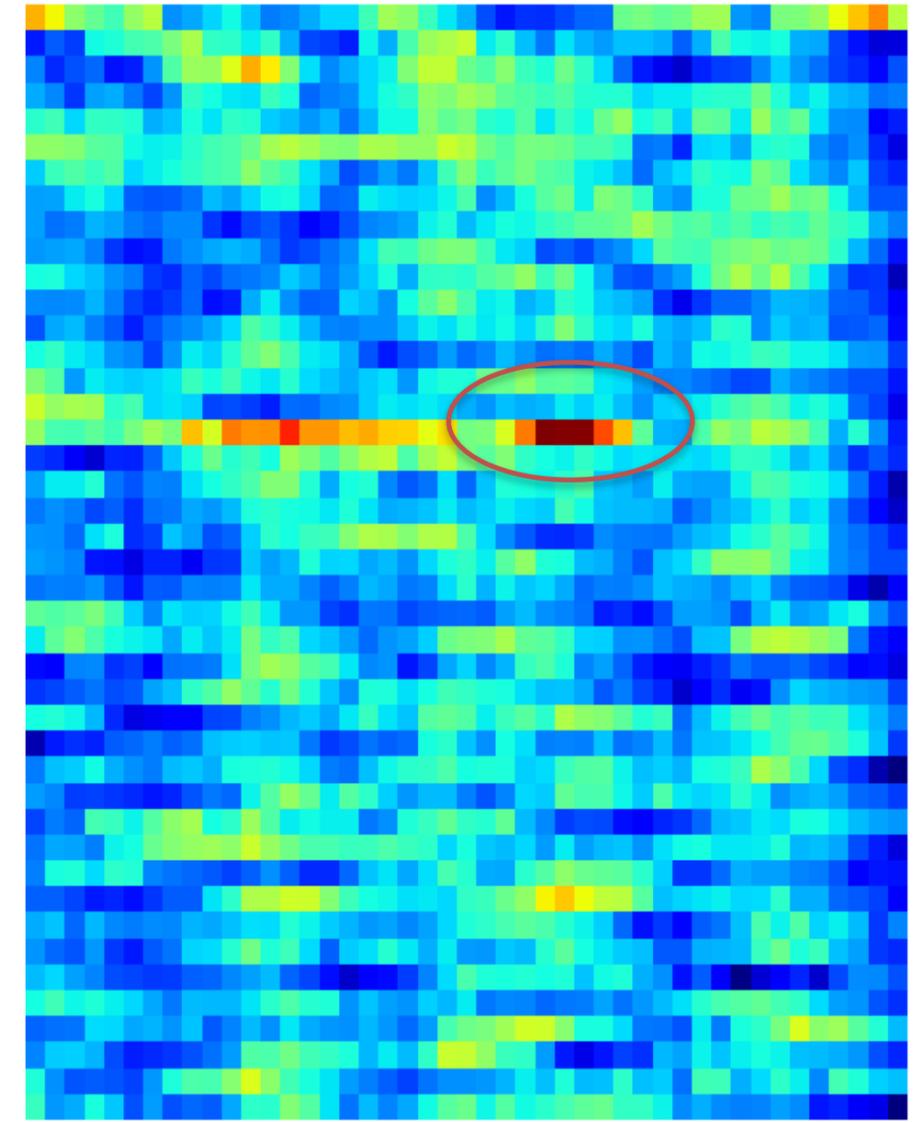
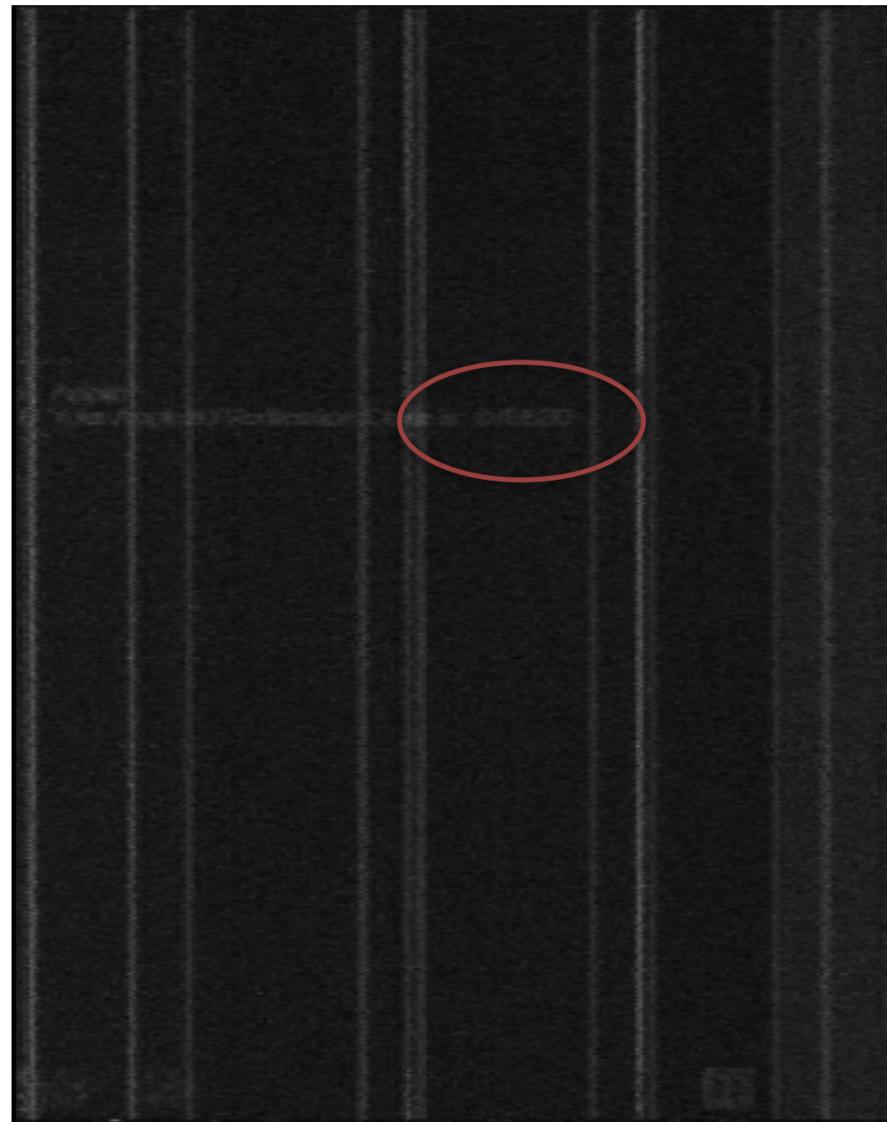
# Finding the Security Code



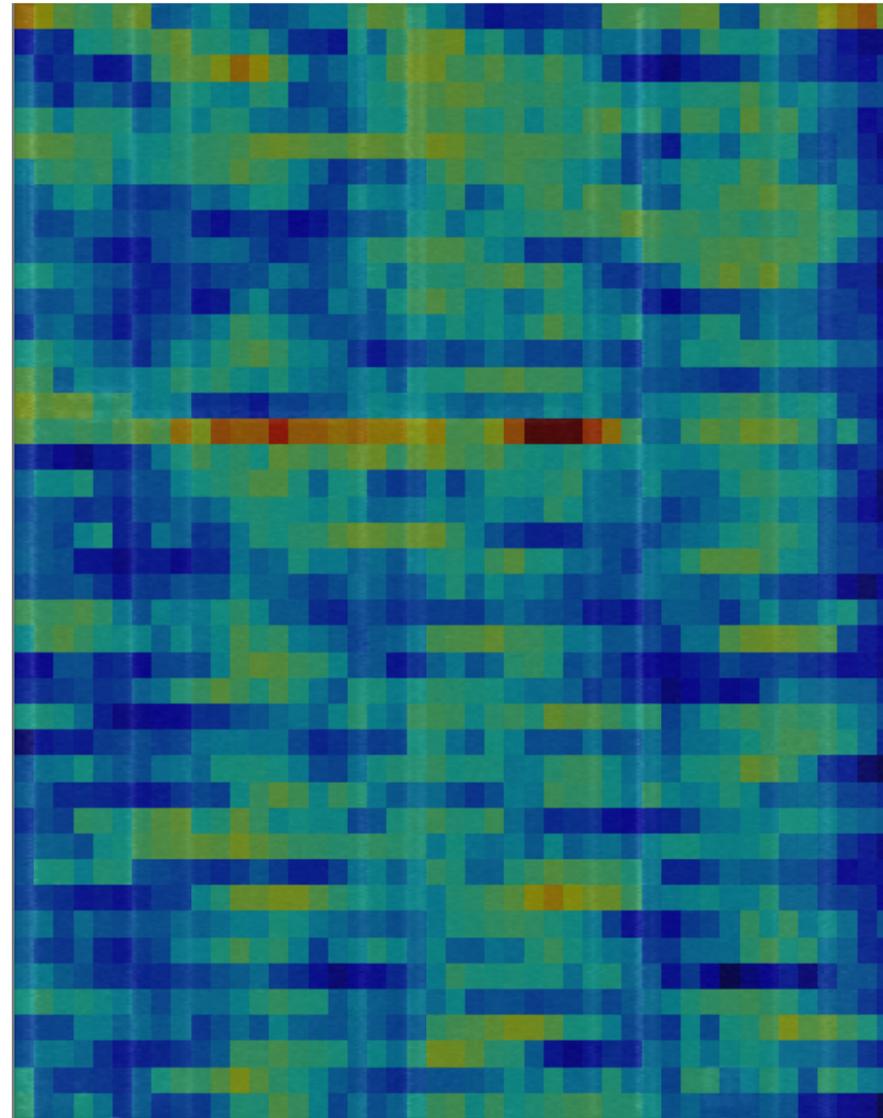
# Finding the Security Code



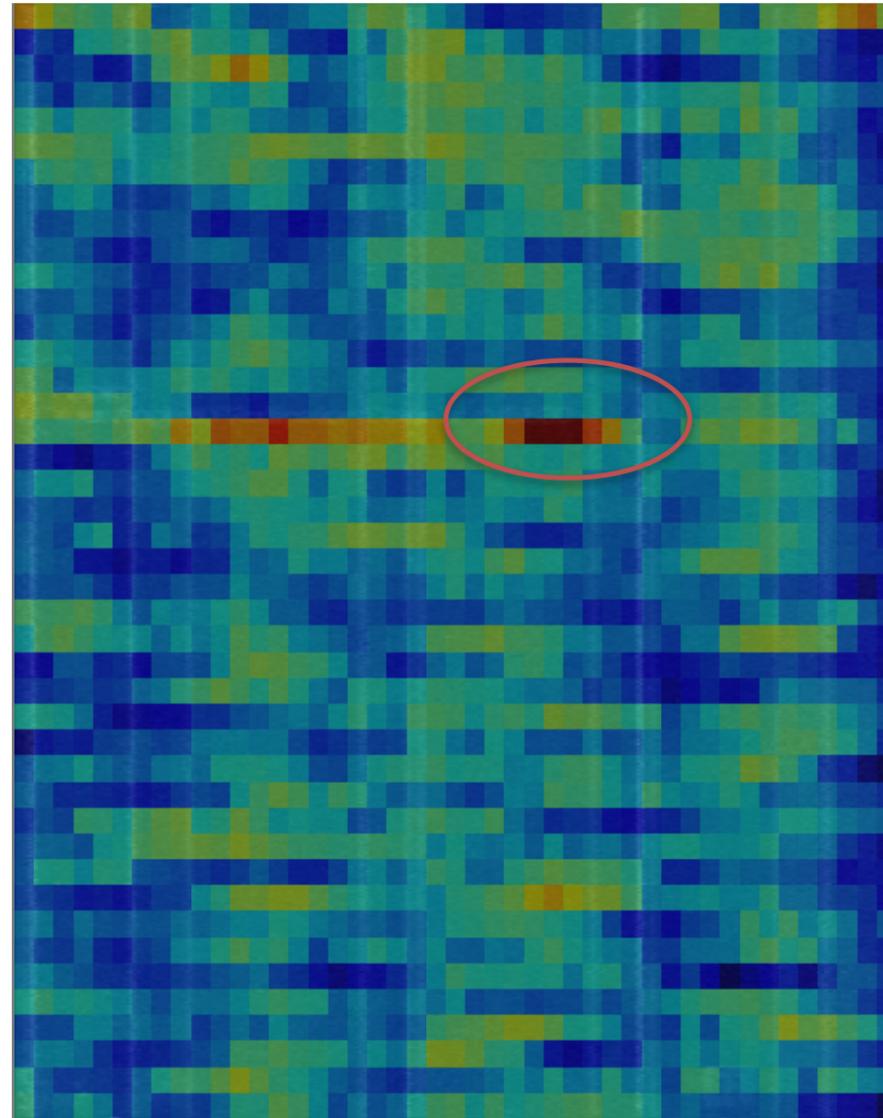
# Finding the Security Code



# Finding the Security Code



# Finding the Security Code



# Obtaining Training Data

# Obtaining Training Data

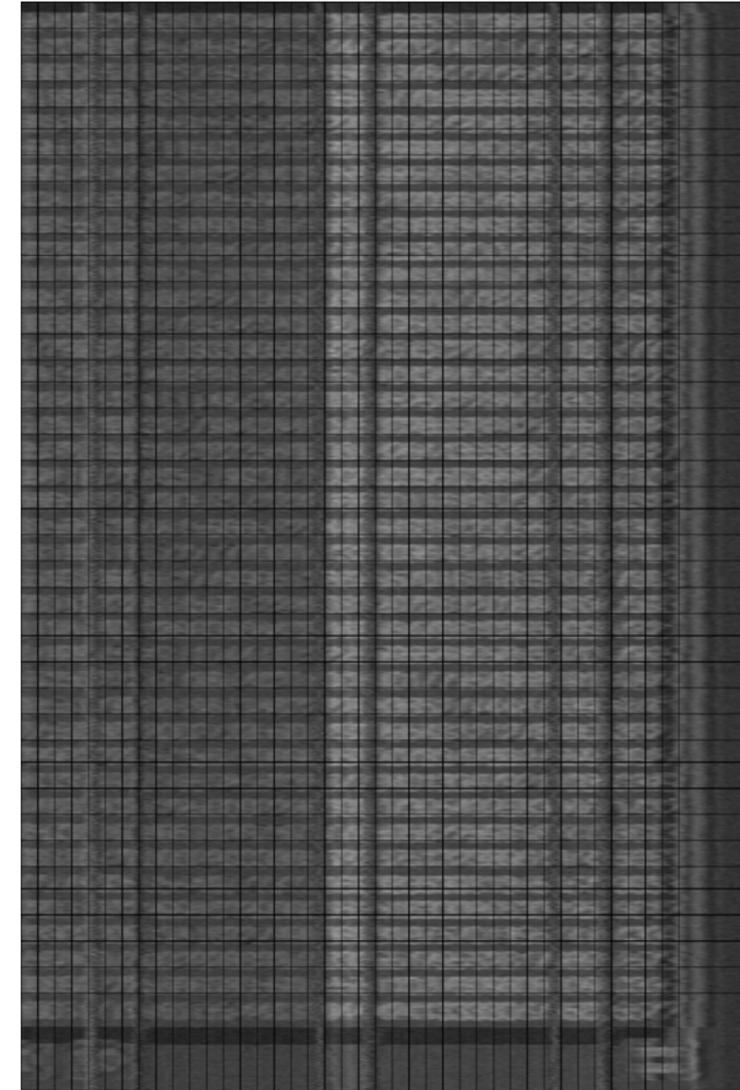
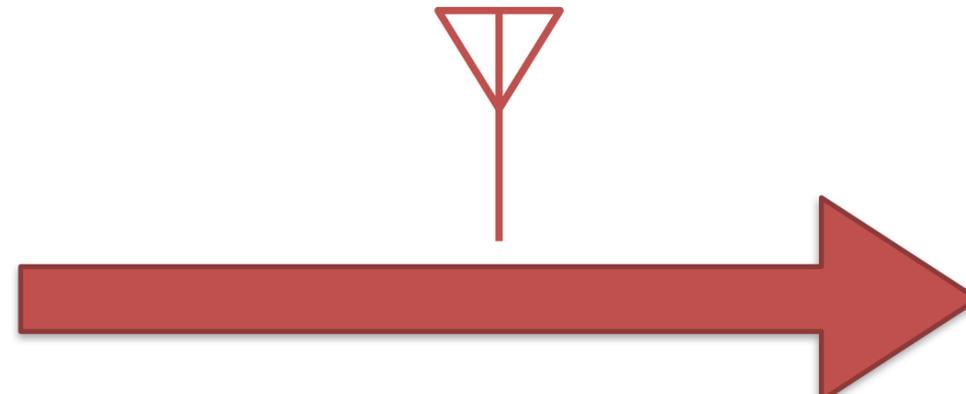
Apple  
Your Apple ID Verification Code is: 129891

# Obtaining Training Data

```
2006924780848347385478692204307546121785  
5431073465095921124896941864764126527355  
7131454994071891222627626360772746660352  
3840316182082719281174448224893704526464  
9737243035769861919822729033781988816161  
0996084426830362823429371356797466527563  
4581695673644710211764135414605818790272  
2491087223550525958043268843772397507247  
5482590668403905864266401008395311548150  
7530353995241915809129785190961147310738  
1233441951743776760815049281918449740261  
2367589038139540974465272314454573563522  
8203965420599962671061396570774783878894  
1886963625198156125828624344477440928861  
7748131783134297136009733640610868019904  
7920585395388811932924947545082443364727  
9692175084905105595918393583739880826180  
5937234374717140337031366315230738636240  
0169867391856543559360534572885461753652  
1306426042220854894929643087111741454784  
5735248412009960870397645976091421702090  
9482288180674574070540535082944666436749  
5208631499268993204706789166552615791789  
6934709176842943962383007548043352722860  
0783603118671323756042826121239734263951  
4703586656712646920321580832950634467458  
8004080643927477341848310752978052946120  
2387703774297921113425761890583182478059  
1999806781864168507538220083989284559285  
7415463301859804840483214642737577287831  
7617300604062365060823342965065261568234  
2296856443865008692446625697585972450723  
8280456393580485317803249478978260642527  
0670812873594642054573975318773092056222  
6020506987237505639416485125836504706472  
7279195080043692185728610531861015857085  
6720100262081288719887092286688911908363  
6148987014821473130261217380895552391873  
6459002653576803159054977563889918324100  
5339581974519127375237816898826189546399
```

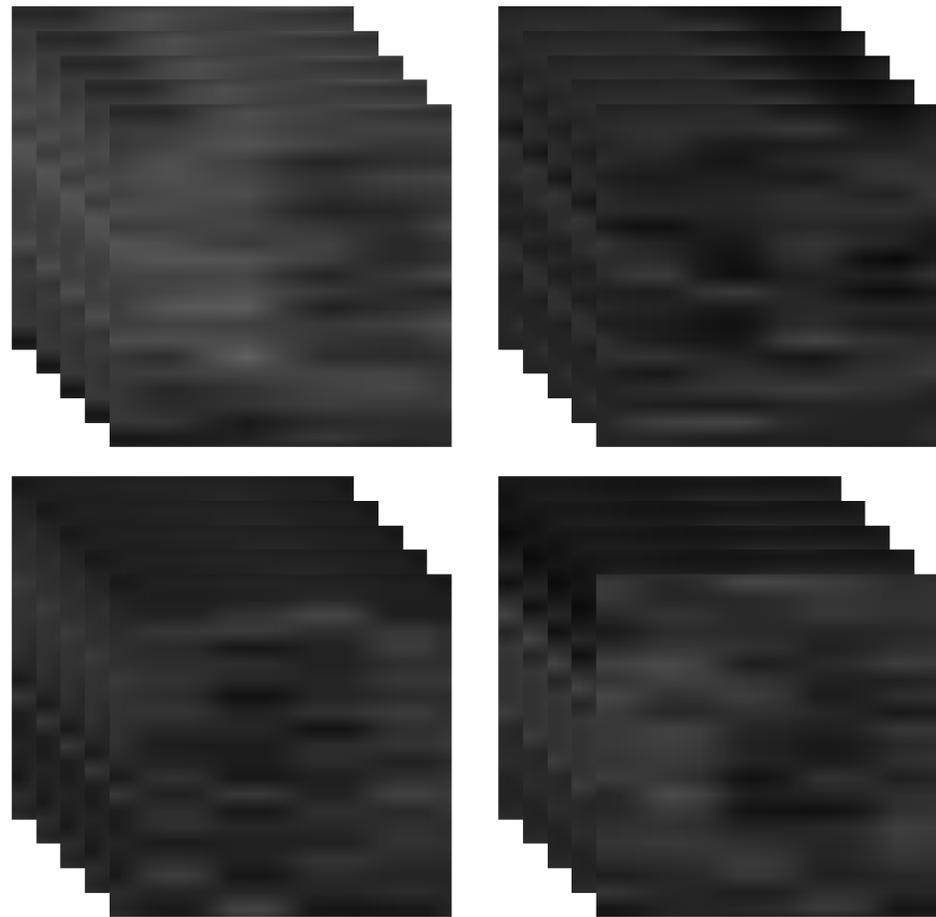
# Obtaining Training Data

```
2006924780848347385478692204307546121785  
5431073465095921124896941864764126527355  
7131454994071891222627626360772746660352  
3840316182082719281174448224893704526464  
9737243035769861919822729033781988816161  
0996084426830362823429371356797466527563  
4581695673644710211764135414605818790272  
2491087223550525958043268843772397507247  
5482590668403905864266401008395311548150  
7530353995241915809129785190961147310738  
1233441951743776760815049281918449740261  
2367589038139540974465272314454573563522  
8203965420599962671061396570774783878894  
1886963625198156125828624344477440928861  
7748131783134297136009733640610868019904  
7920585395388811932924947545082443364727  
9692175084905105595918393583739880826180  
5937234374717140337031366315230738636240  
0169867391856543559360534572885461753652  
1306426042220854894929643087111741454784  
5735248412009960870397645976091421702090  
9482288180674574070540535082944666436749  
5208631499268993204706789166552615791789  
6934709176842943962383007548043352722860  
0783603118671323756042826121239734263951  
4703586656712646920321580832950634467458  
8004080643927477341848310752978052946120  
2387703774297921113425761890583182478059  
1999806781864168507538220083989284559285  
7415463301859804840483214642737577287831  
7617300604062365060823342965065261568234  
2296856443865008692446625697585972450723  
8280456393580485317803249478978260642527  
0670812873594642054573975318773092056222  
6020506987237505639416485125836504706472  
7279195080043692185728610531861015857085  
6720100262081288719887092286688911908363  
6148987014821473130261217380895552391873  
6459002653576803159054977563889918324100  
5339581974519127375237816898826189546399
```



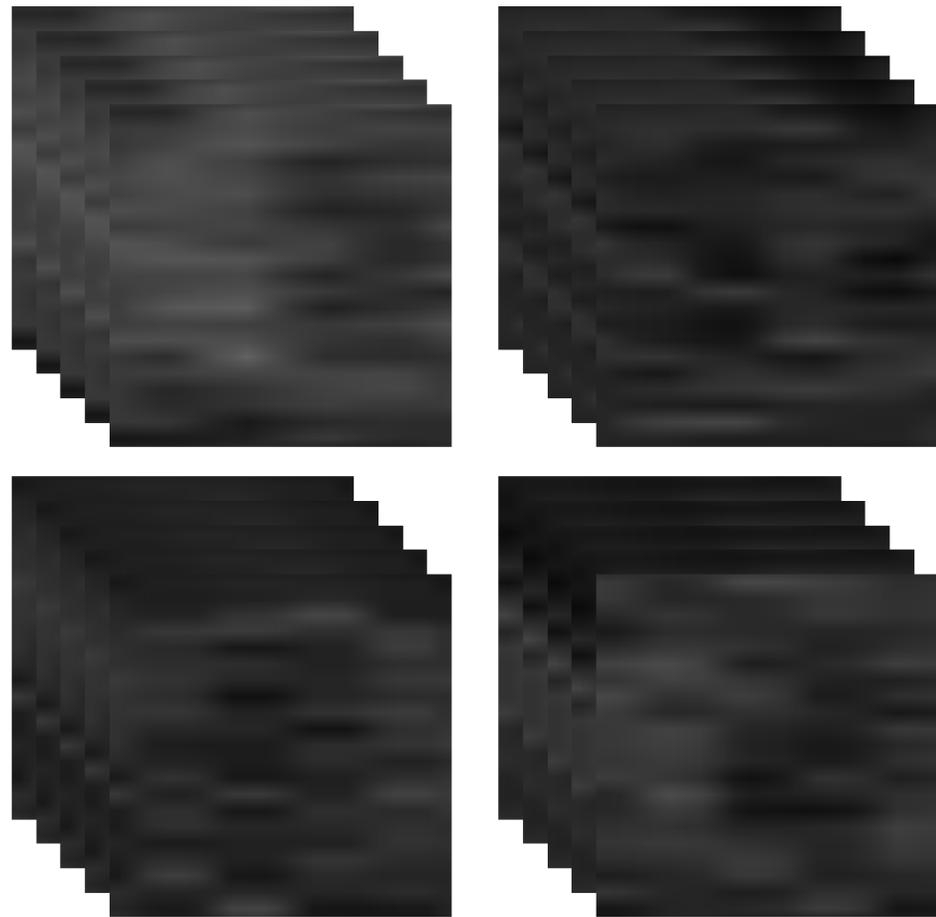
# Machine Learning Training

# Machine Learning Training



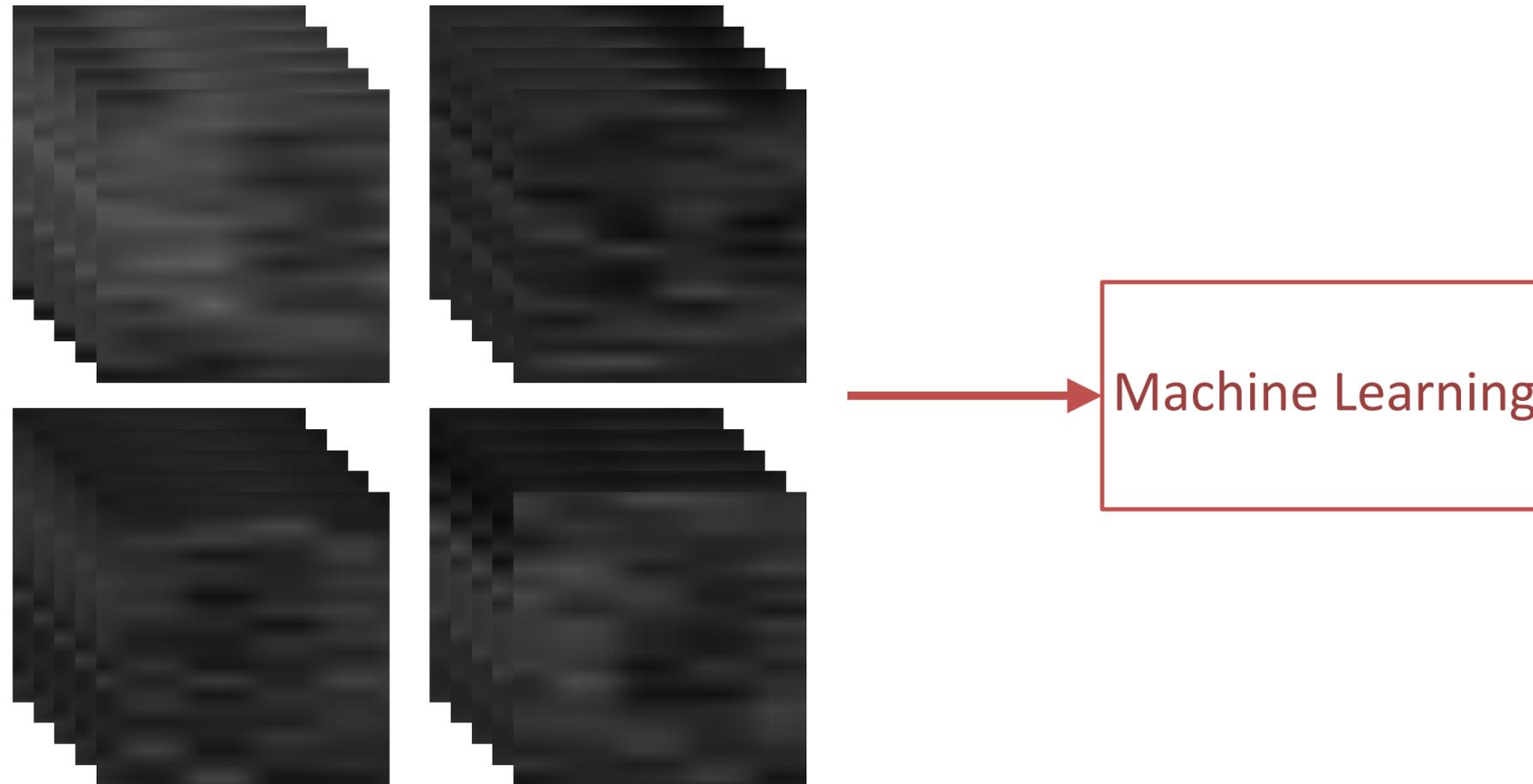
# Machine Learning Training

*"This is a digit 0"*

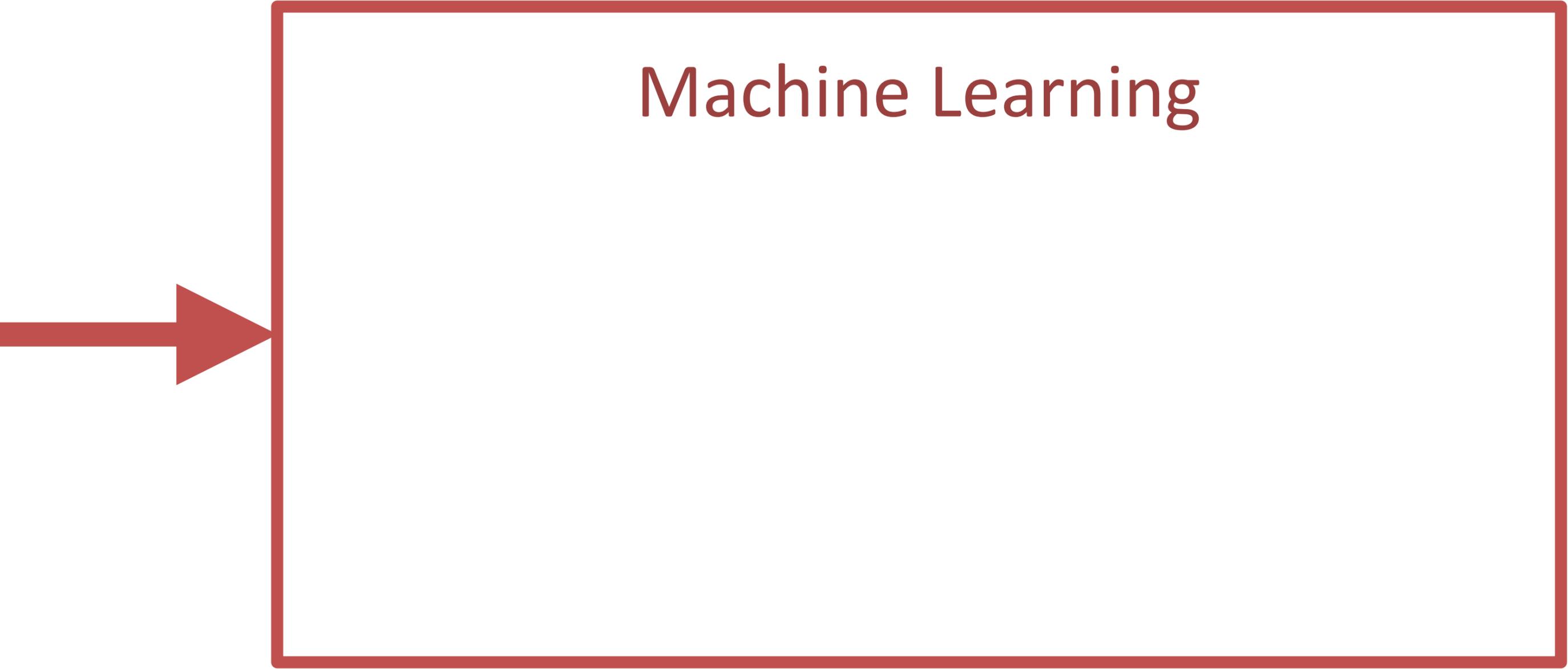


# Machine Learning Training

*"This is a digit 0"*

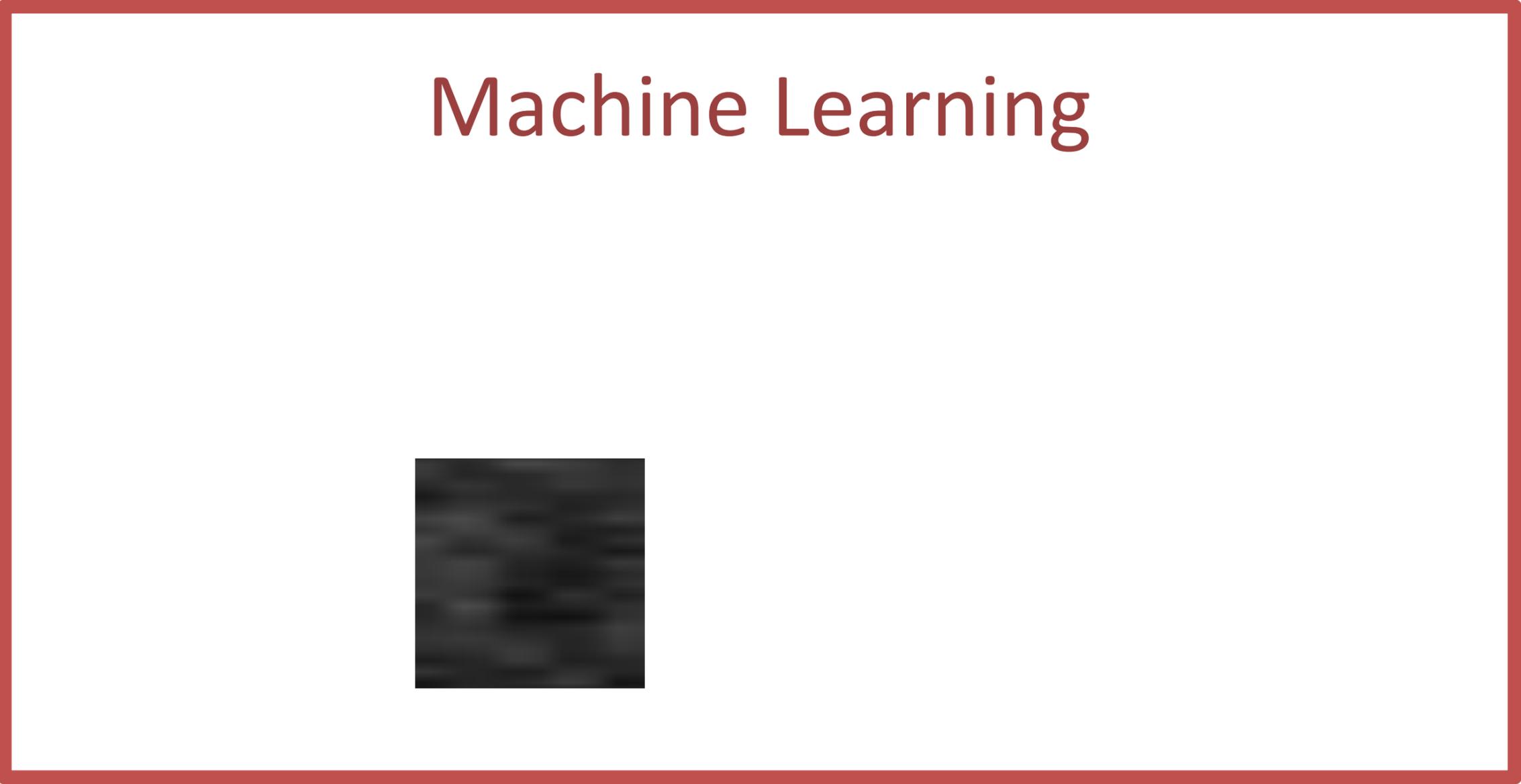


# Machine Learning Training



Machine Learning

# Machine Learning Training



Machine Learning

# Machine Learning Training

Machine Learning



*"This is a digit 0"*

# Machine Learning Training

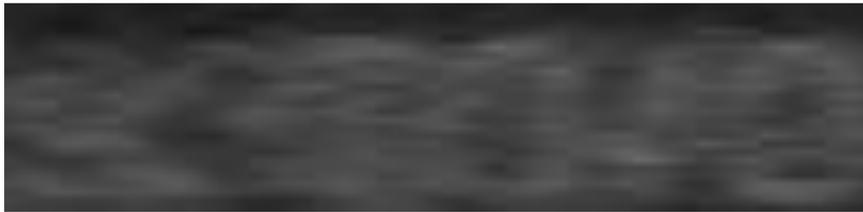
Machine Learning

A 0 looks like



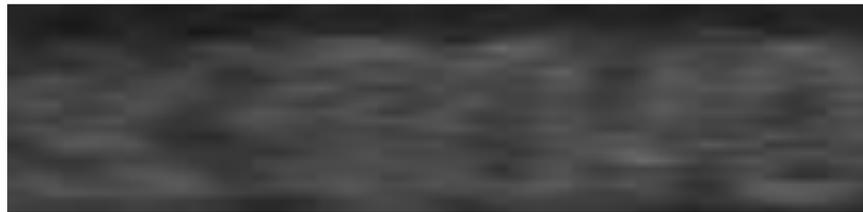
# Machine Learning Classification

# Machine Learning Classification



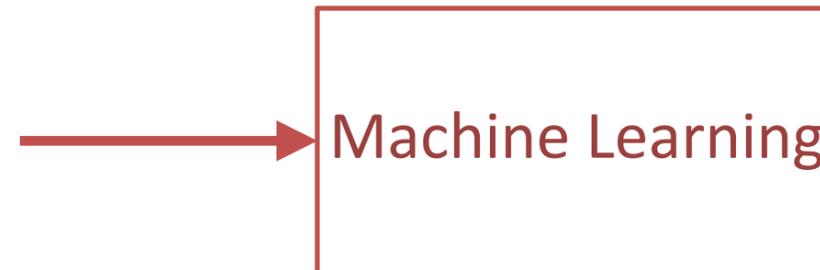
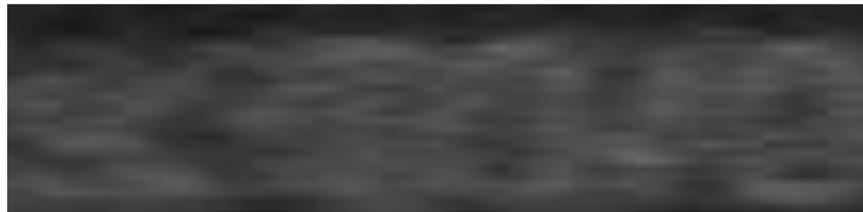
# Machine Learning Classification

*“What does this say?”*



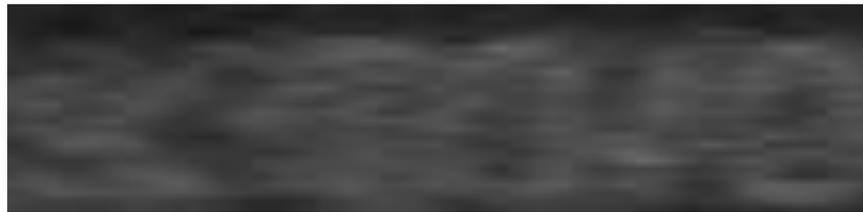
# Machine Learning Classification

*“What does this say?”*



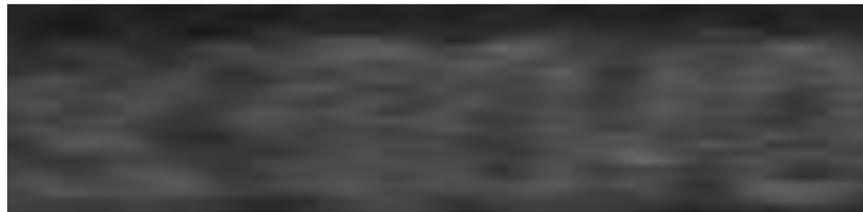
# Machine Learning Classification

*“What does this say?”*

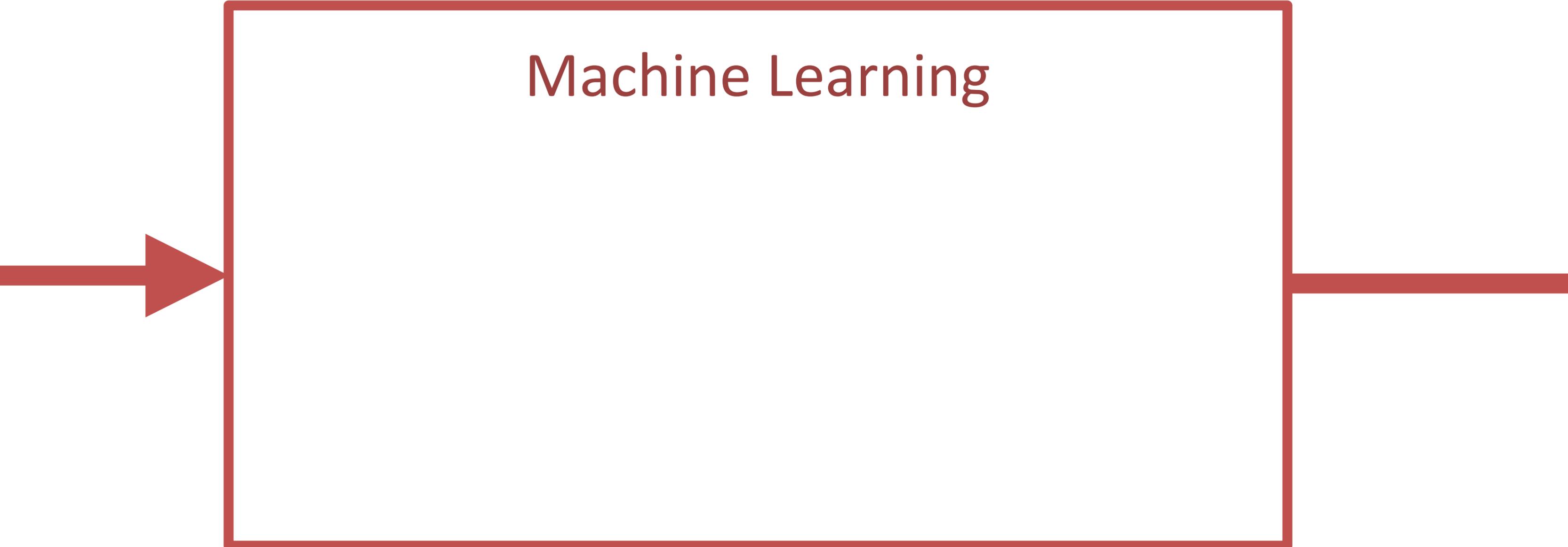


# Machine Learning Classification

*“What does this say?”*



# Machine Learning Classification

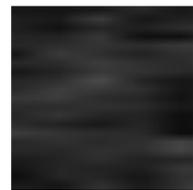
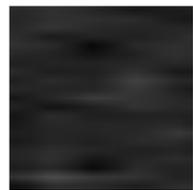
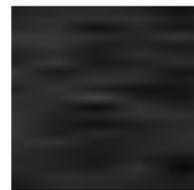
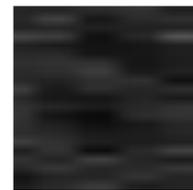


Machine Learning

# Machine Learning Classification

## Machine Learning

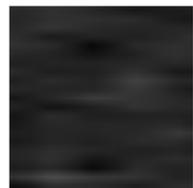
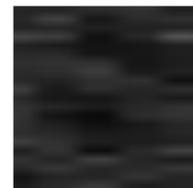
A 6      An 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



# Machine Learning Classification

## Machine Learning

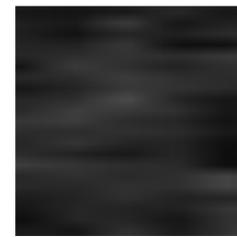
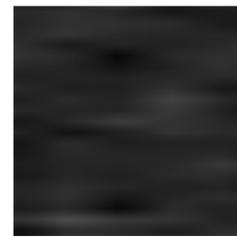
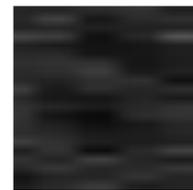
A 6      A n 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



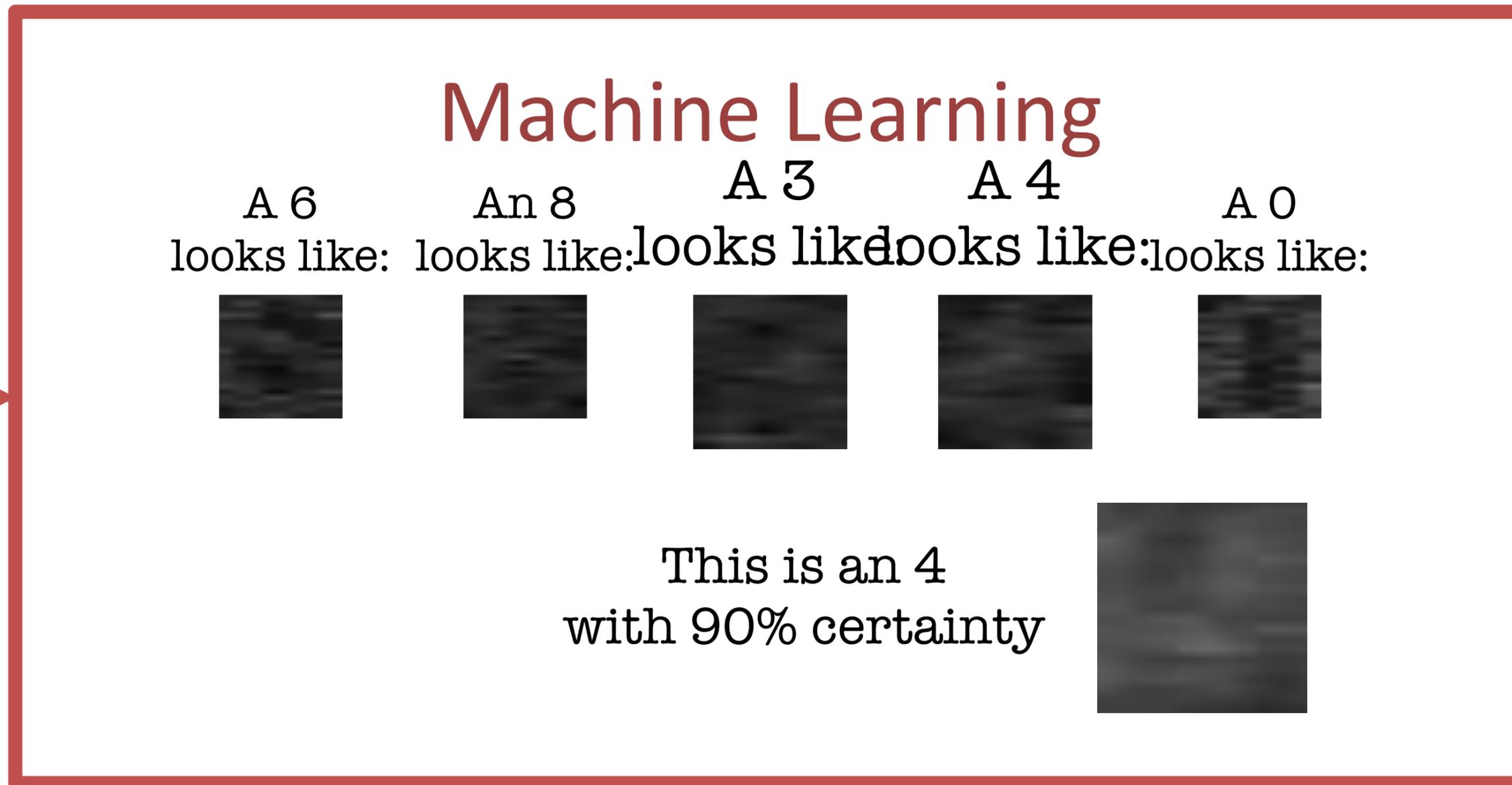
# Machine Learning Classification

## Machine Learning

A 6      A n 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



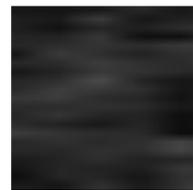
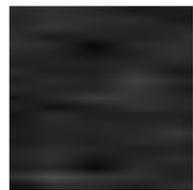
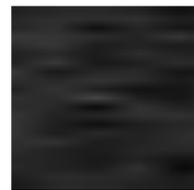
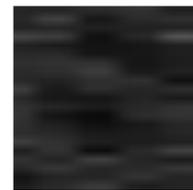
# Machine Learning Classification



# Machine Learning Classification

## Machine Learning

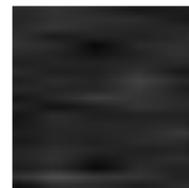
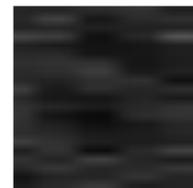
A 6      An 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



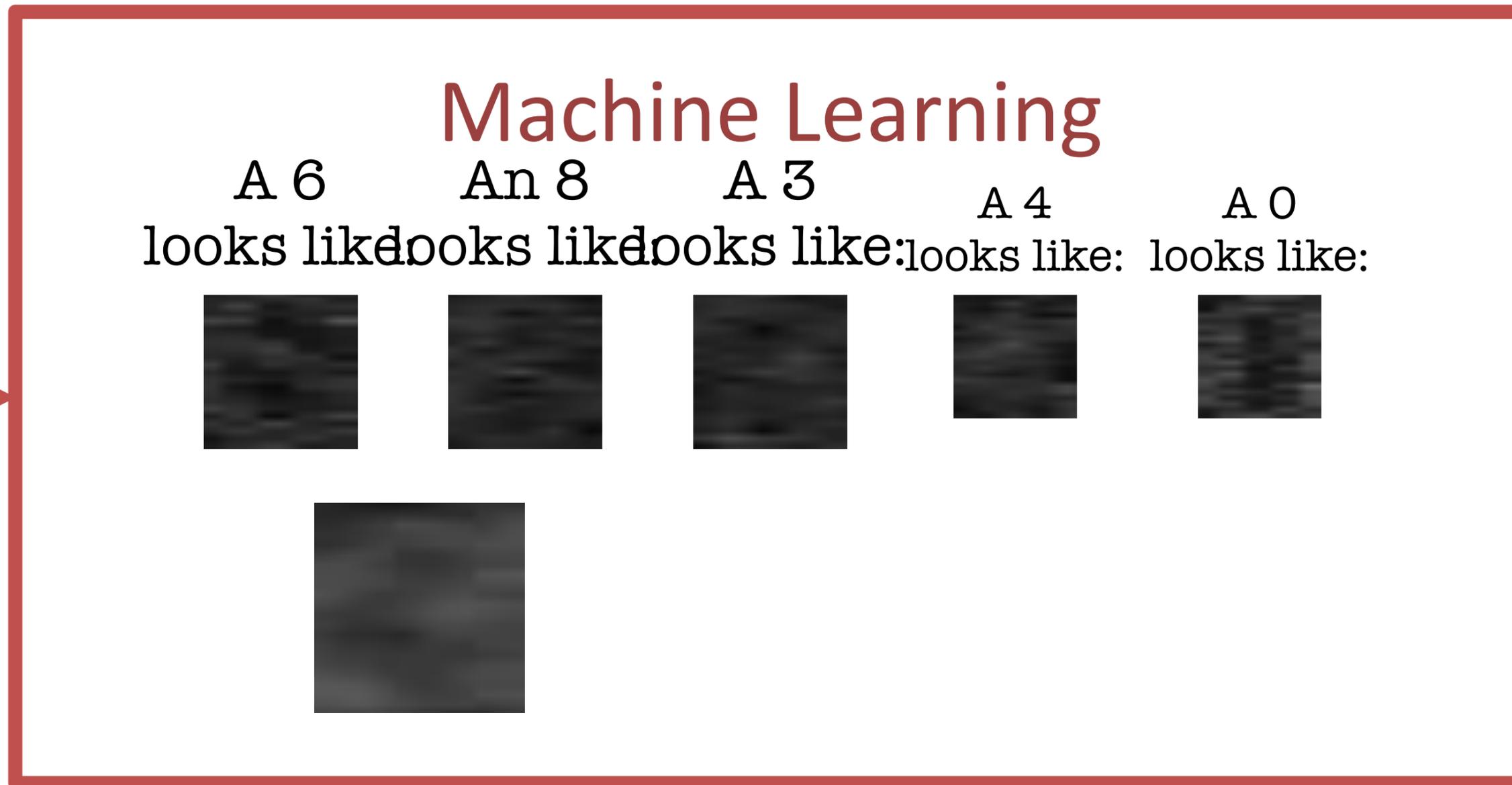
# Machine Learning Classification

## Machine Learning

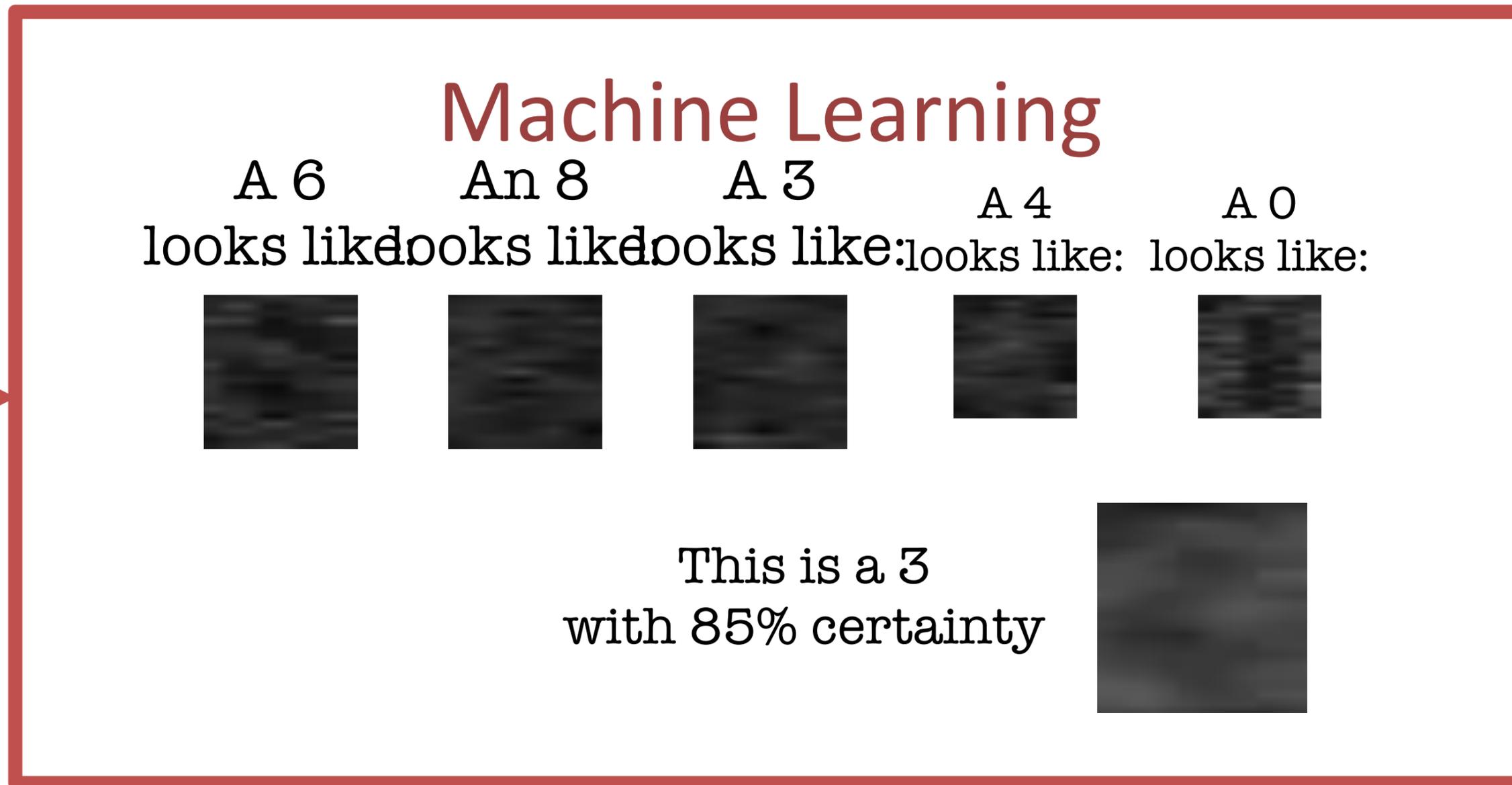
A 6      A n 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



# Machine Learning Classification



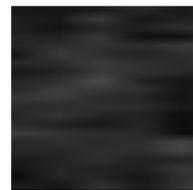
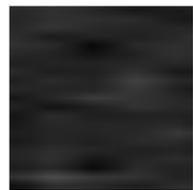
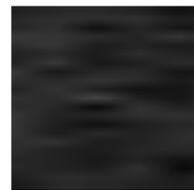
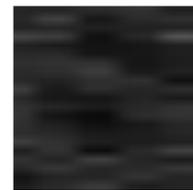
# Machine Learning Classification



# Machine Learning Classification

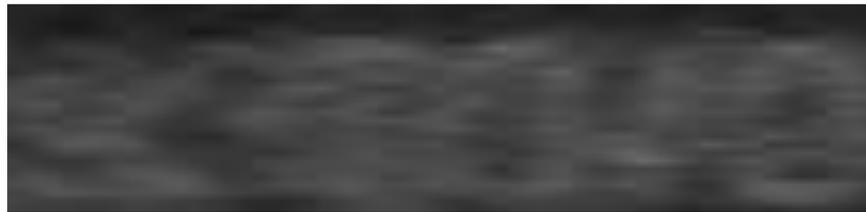
## Machine Learning

A 6      An 8      A 3      A 4      A 0  
looks like: looks like: looks like: looks like: looks like:



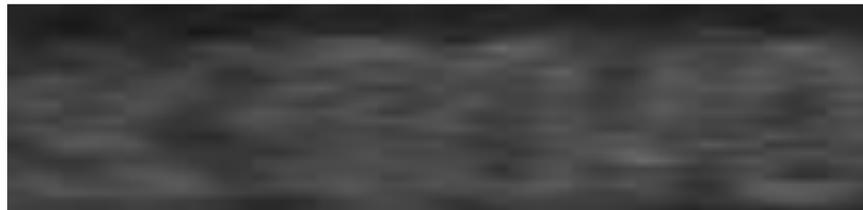
# Machine Learning Classification

*“What does this say?”*



# Machine Learning Classification

*“What does this say?”*



I am 90% sure  
it is “937042”.

# OUTLOOK

# Outlook

# Outlook

- Non-ideal antenna

# Outlook

- Non-ideal antenna
  - Want to measure greater distances

# Outlook

- Non-ideal antenna
  - Want to measure greater distances
  - Want to measure every phone

# Outlook

- Non-ideal antenna
  - Want to measure greater distances
  - Want to measure every phone
- SDR setup requires optimizations

# Outlook

- Non-ideal antenna
  - Want to measure greater distances
  - Want to measure every phone
- SDR setup requires optimizations
  - Higher sample rates

# Outlook

- Non-ideal antenna
  - Want to measure greater distances
  - Want to measure every phone
- SDR setup requires optimizations
  - Higher sample rates
  - Other measurement methods

# Outlook

- Non-ideal antenna
  - Want to measure greater distances
  - Want to measure every phone
- SDR setup requires optimizations
  - Higher sample rates
  - Other measurement methods
- New testbed for machine learning

# Take Home Message...

# Take Home Message...

**Screen Gleaning works!**

# Take Home Message...

**Screen Gleaning works!**

**Be careful with what you read on your phone...**

# DISCUSSION







