Signals and Systems

Lecture 10: Bode Diagrams

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Zhejiang University

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Partly adapted from the materials provided on the MIT OpenCourseWare

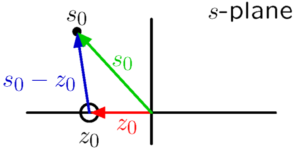
Review

Complex exponentials are eigenfunctions of LTI systems.

$$e^{s_0 t} \longrightarrow \boxed{H(s)} \longrightarrow H(s_0)\, e^{s_0 t}$$

$H(s_0)$ can be determined graphically using vectorial analysis.

$$H(s_0) = K \frac{(s_0 - z_0)(s_0 - z_1)(s_0 - z_2)\cdots}{(s_0 - p_0)(s_0 - p_1)(s_0 - p_2)\cdots}$$

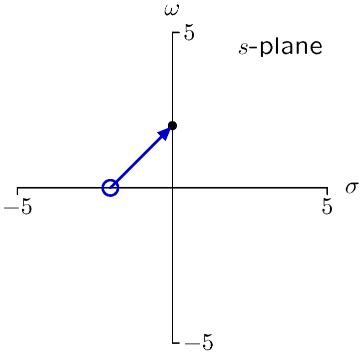


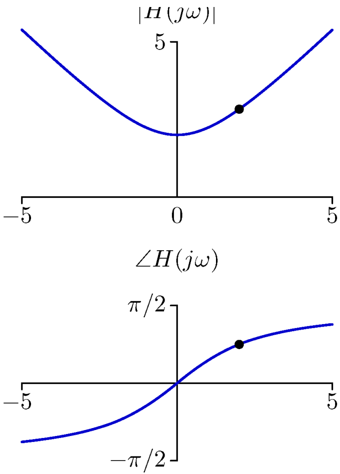
Response of an LTI system to an eternal cosine is an eternal cosine: same frequency, but scaled and shifted.

$$\cos(\omega_0 t) \longrightarrow \boxed{H(s)} \longrightarrow |H(j\omega_0)| \cos\big(\omega_0 t + \angle H(j\omega_0)\big)$$

Frequency Response: $H(s)|_{s \leftarrow j\omega}$

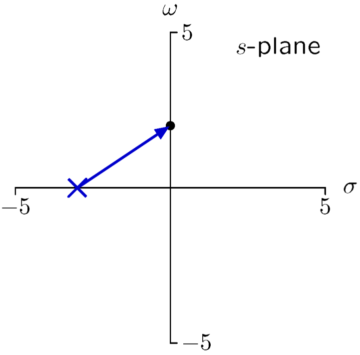
$$H(s) = s - z_1$$

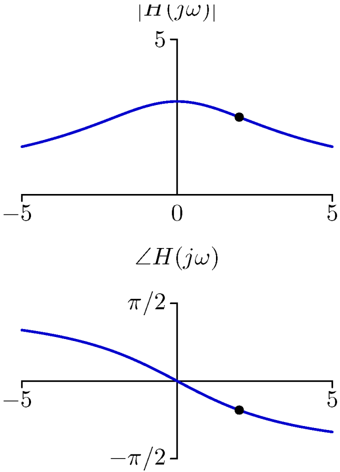




Frequency Response: $H(s)|_{s \leftarrow j\omega}$

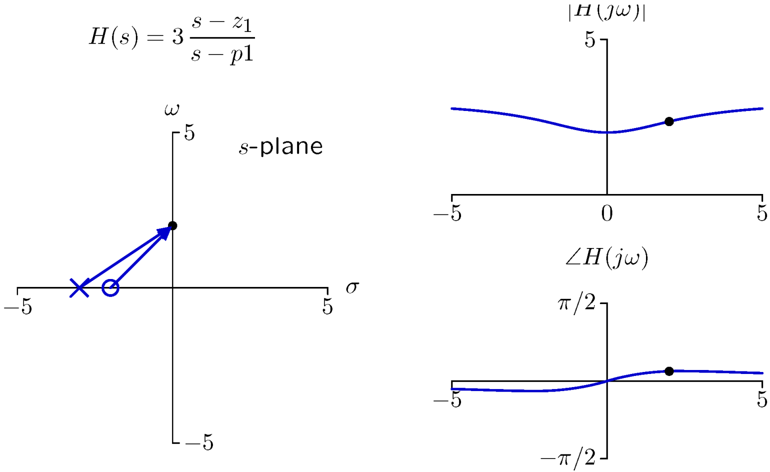
$$H(s) = \frac{9}{s - p_1}$$





Frequency Response: $H(s)|_{s \leftarrow j\omega}$

$$H(s) = 3\,\frac{s - z_1}{s - p1}$$



Poles and Zeros

Thinking about systems as collections of poles and zeros is an important design concept.

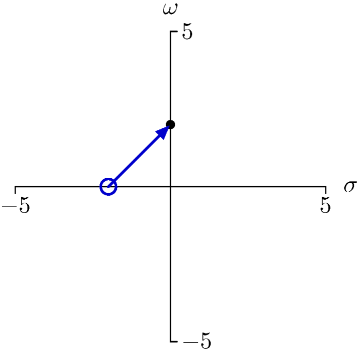
- simple: just a few numbers characterize entire system
- powerful: complete information about frequency response

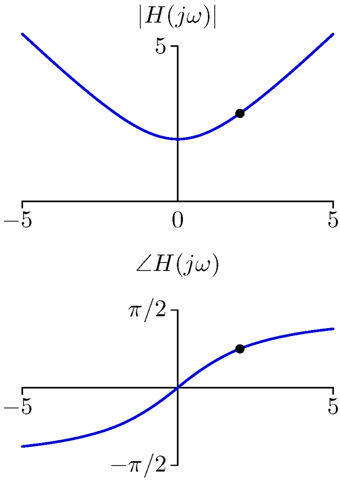
Today: poles, zeros, frequency responses, and Bode plots.

Asymptotic Behavior: Isolated Zero

The magnitude response is simple at low and high frequencies.

$$H(j\omega) = j\omega - z_1$$





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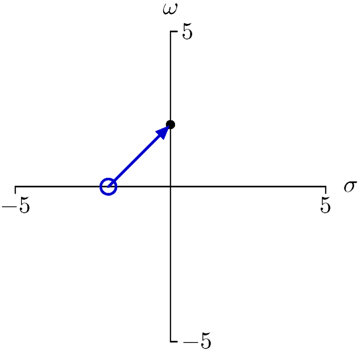

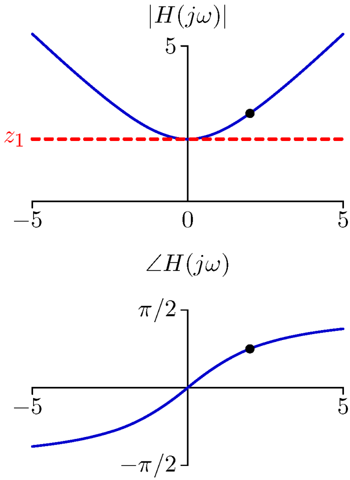

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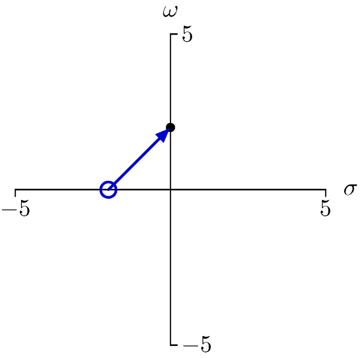
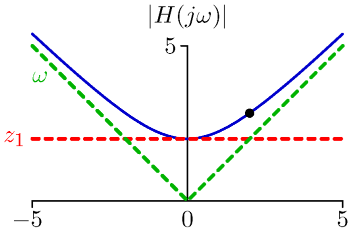
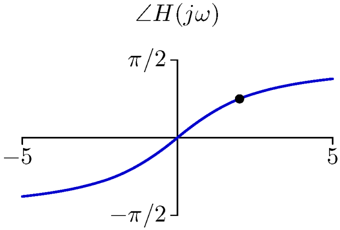


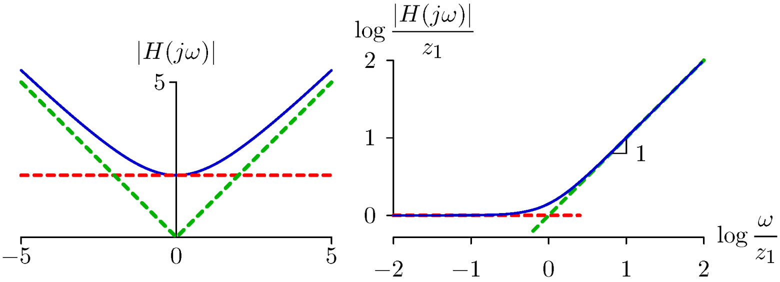




Asymptotic Behavior: Isolated Zero

Two asymptotes provide a good approxmation on log-log axes.

$$H(s) = s - z_1$$



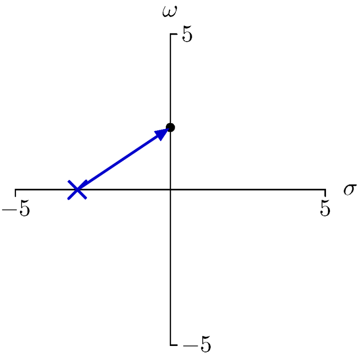
$$\lim_{\omega \to 0} |H(j\omega)| = z_1$$

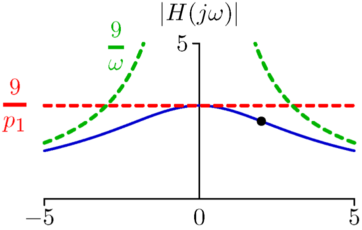
$$\lim_{\omega \to \infty} |H(j\omega)| = \omega$$

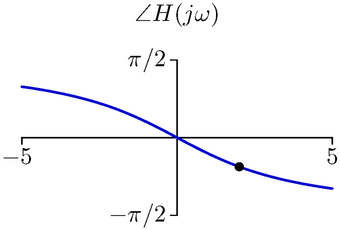
Asymptotic Behavior: Isolated Pole

The magnitude response is simple at low and high frequencies.

$$H(s) = \frac{9}{s - p_1}$$







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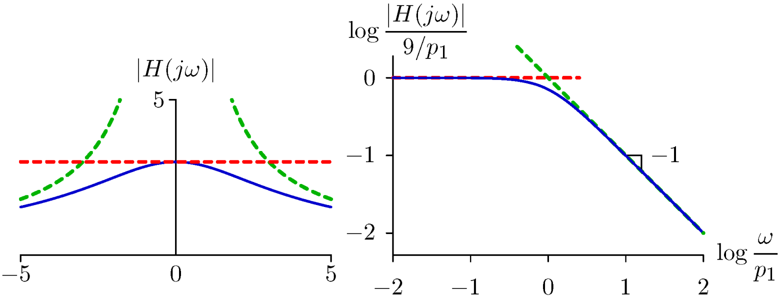

$$\lim_{\omega \to 0} |H(j\omega)| = \frac{9}{p_1}$$

$$\lim_{\omega \to \infty} |H(j\omega)| = \frac{9}{\omega}$$

Check Yourself

Compare log-log plots of the frequency-response magnitudes of the following system functions:

$$H_1(s) = \frac{1}{s+1} \qquad \text{and} \qquad H_2(s) = \frac{1}{s+10}$$

The former can be transformed into the latter by

1. shifting horizontally
2. shifting and scaling horizontally
3. shifting both horizontally and vertically
4. shifting and scaling both horizontally and vertically
5. none of the above

Check Yourself

Compare log-log plots of the frequency-response magnitudes of the following system functions:

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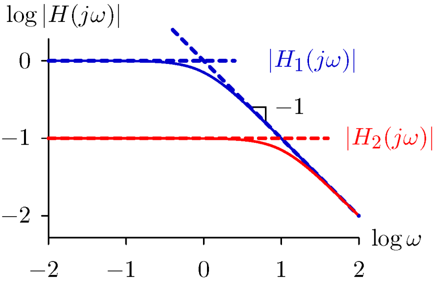

Check Yourself

Compare log-log plots of the frequency-response magnitudes of the following system functions:

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The former can be transformed into the latter by 3

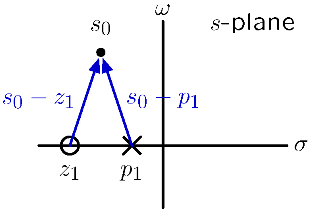
1. shifting horizontally
2. shifting and scaling horizontally
3. shifting both horizontally and vertically
4. shifting and scaling both horizontally and vertically
5. none of the above

no scaling in either vertical or horizontal directions !

Asymptotic Behavior of More Complicated Systems

Constructing $H(s_0)$.

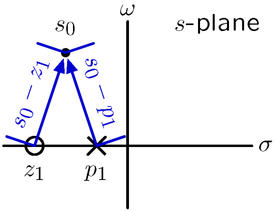
$$H(s_0) = K \frac{\displaystyle\prod_{q=1}^{Q}(s_0 - z_q)}{\displaystyle\prod_{p=1}^{P}(s_0 - p_p)} \quad \begin{array}{l} \leftarrow \text{ product of vectors for zeros} \\ \\ \leftarrow \text{ product of vectors for poles} \end{array}$$



Asymptotic Behavior of More Complicated Systems

The magnitude of a product is the product of the magnitudes.

$$|H(s_0)| = \left| K \frac{\prod_{q=1}^{Q}(s_0 - z_q)}{\prod_{p=1}^{P}(s_0 - p_p)} \right| = |K| \frac{\prod_{q=1}^{Q}|s_0 - z_q|}{\prod_{p=1}^{P}|s_0 - p_p|}$$



Bode Plot

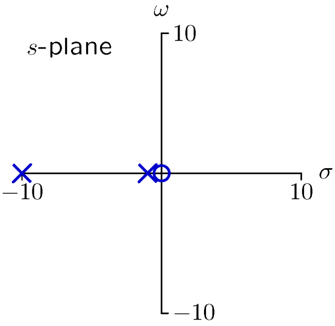
The log of the magnitude is a sum of logs.

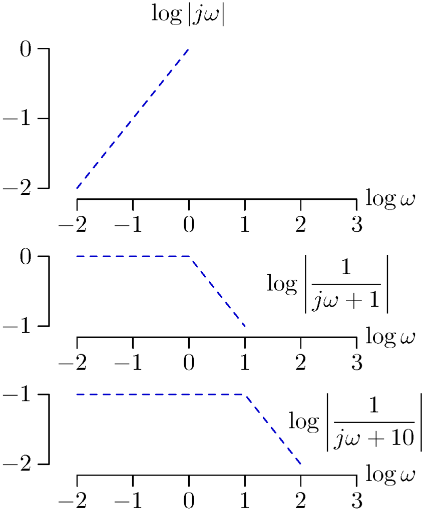
$$|H(s_0)| = \left| K \frac{\prod_{q=1}^{Q} (s_0 - z_q)}{\prod_{p=1}^{P} (s_0 - p_p)} \right| = |K| \frac{\prod_{q=1}^{Q} |s_0 - z_q|}{\prod_{p=1}^{P} |s_0 - p_p|}$$

$$\log |H(j\omega)| = \log |K| + \sum_{q=1}^{Q} \log |j\omega - z_q| - \sum_{p=1}^{P} \log |j\omega - p_p|$$

Bode Plot: Adding Instead of Multiplying

$$H(s) = \frac{s}{(s+1)(s+10)}$$





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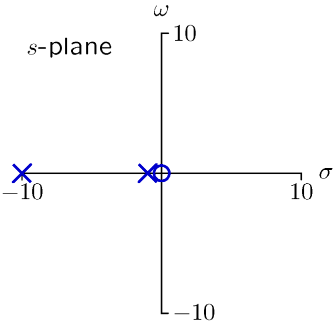

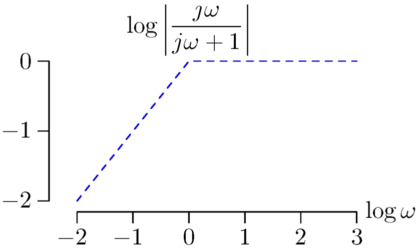

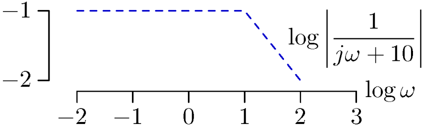

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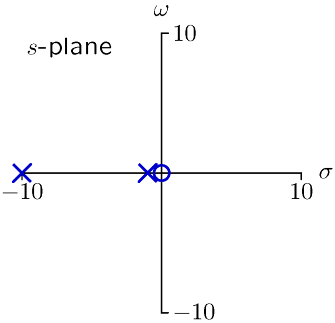

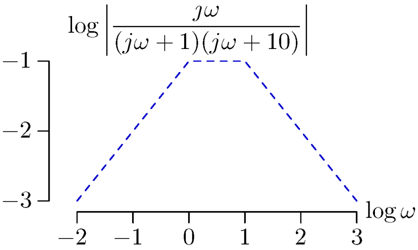

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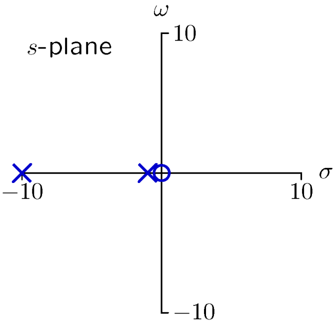
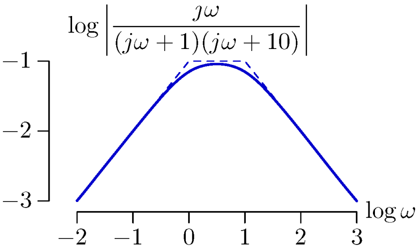
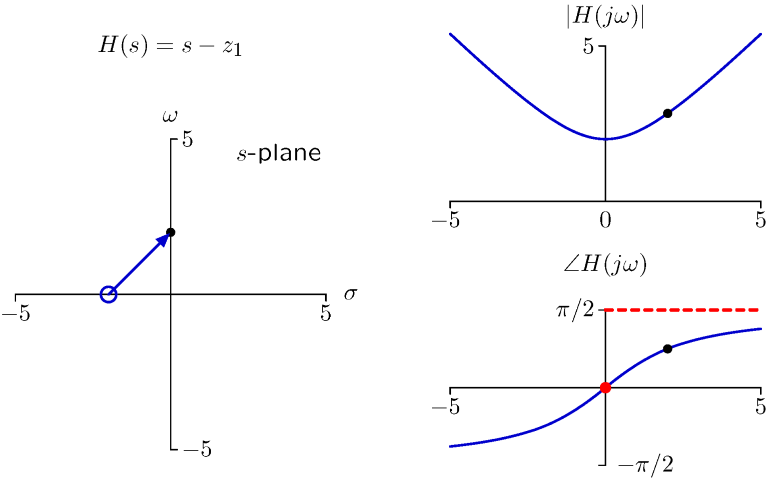




Asymptotic Behavior: Isolated Zero

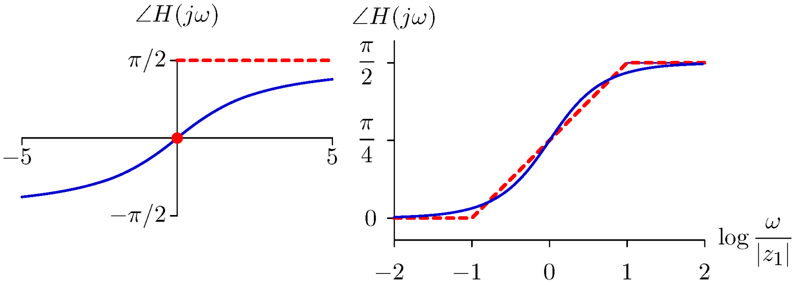
The angle response is simple at low and high frequencies.



Asymptotic Behavior: Isolated Zero

Three straight lines provide a good approxmation versus log ω.

$$H(s) = s - z_1$$



$$\lim_{\omega \to 0} \angle H(j\omega) = 0$$

$$\lim_{\omega \to \infty} \angle H(j\omega) = \pi/2$$

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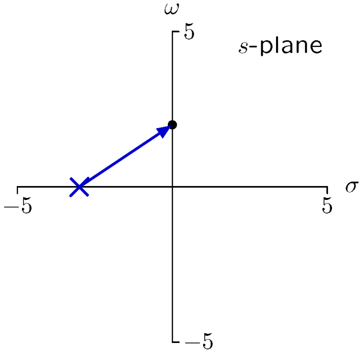

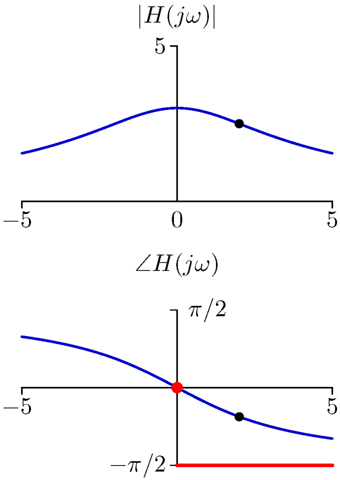

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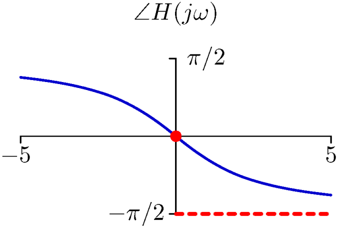
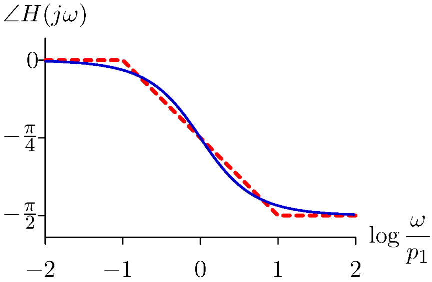




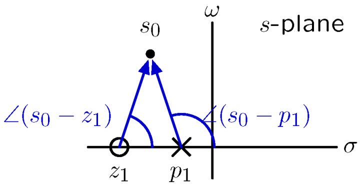
$$\lim_{\omega \to 0} \angle H(j\omega) = 0$$

$$\lim_{\omega \to \infty} \angle H(j\omega) = -\pi/2$$

Bode Plot

The angle of a product is the sum of the angles.

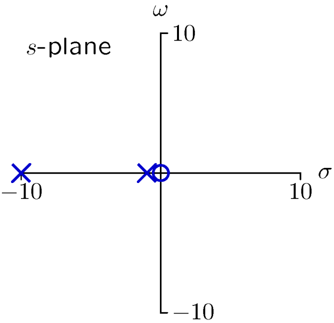
$$\angle H(s_0) = \angle \left(K \frac{\prod_{q=1}^{Q} (s_0 - z_q)}{\prod_{p=1}^{P} (s_0 - p_p)} \right) = \angle K + \sum_{q=1}^{Q} \angle \left(s_0 - z_q\right) - \sum_{p=1}^{P} \angle \left(s_0 - p_p\right)$$

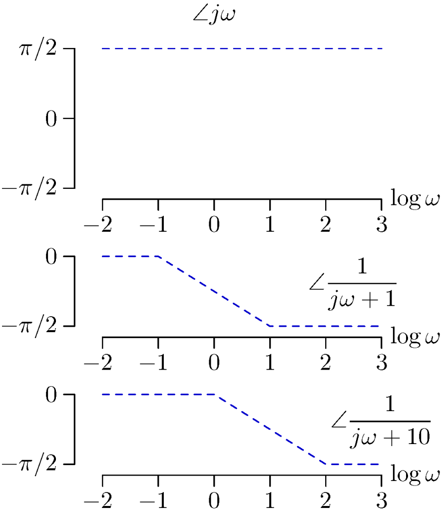


The angle of K can be 0 or π for systems described by linear differential equations with constant, real-valued coefficients.

Bode Plot

$$H(s) = \frac{s}{(s+1)(s+10)}$$





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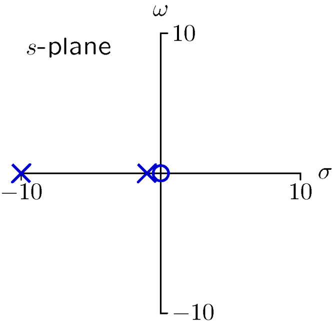

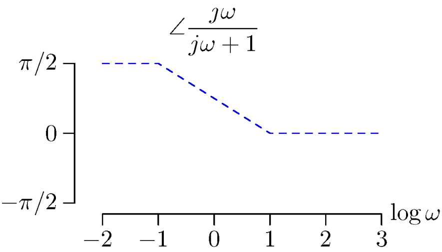

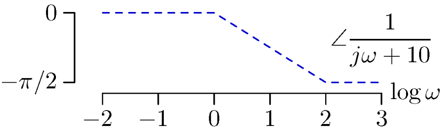

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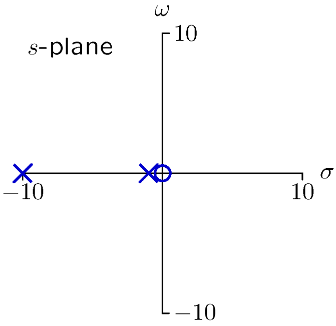

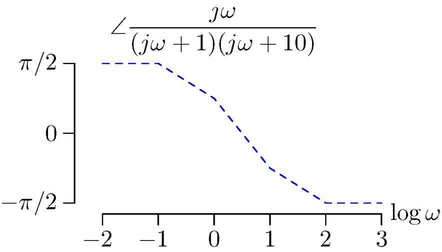

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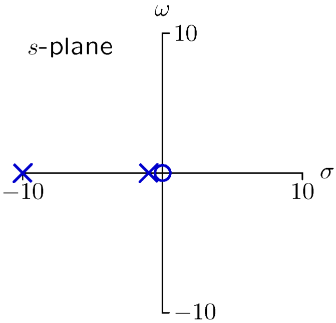
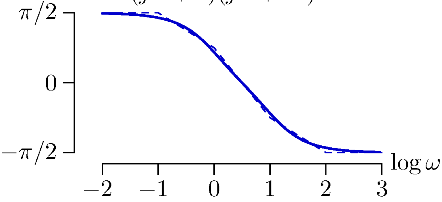




From Frequency Response to Bode Plot

The magnitude of $H(j\omega)$ is a product of magnitudes.

$$|H(j\omega)| = |K| \frac{\displaystyle\prod_{q=1}^{Q} \left|j\omega - z_q\right|}{\displaystyle\prod_{p=1}^{P} \left|j\omega - p_p\right|}$$

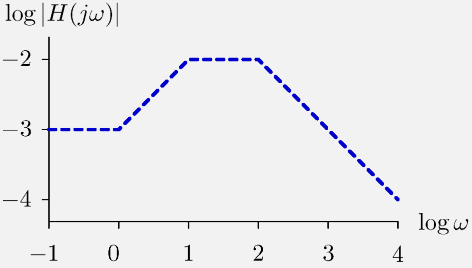
The log of the magnitude is a sum of logs.

$$\log|H(j\omega)| = \log|K| + \sum_{q=1}^{Q} \log\left|j\omega - z_q\right| - \sum_{p=1}^{P} \log\left|j\omega - p_p\right|$$

The angle of $H(j\omega)$ is a sum of angles.

$$\angle H(j\omega) = \angle K + \sum_{q=1}^{Q} \angle\left(j\omega - z_q\right) - \sum_{p=1}^{P} \angle\left(j\omega - p_p\right)$$

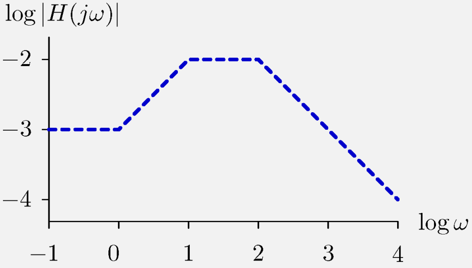
Check Yourself



Which corresponds to the Bode approximation above?

1. $\dfrac{1}{(s+1)(s+10)(s+100)}$
2. $\dfrac{s+1}{(s+10)(s+100)}$
3. $\dfrac{(s+10)(s+100)}{s+1}$
4. $\dfrac{s+100}{(s+1)(s+10)}$
5. none of the above

Check Yourself

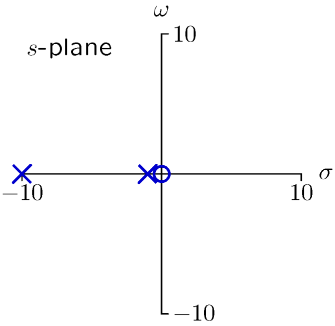


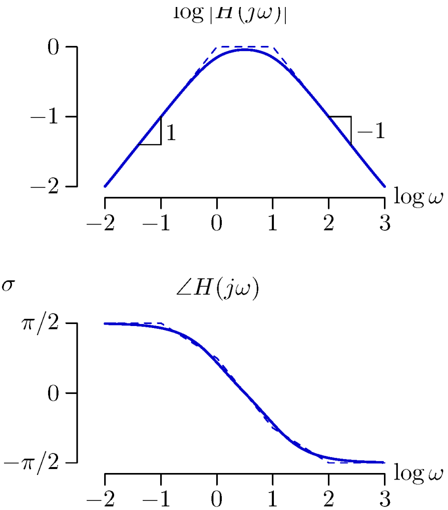
Which corresponds to the Bode approximation above? 2

1. $\dfrac{1}{(s+1)(s+10)(s+100)}$
2. $\dfrac{s+1}{(s+10)(s+100)}$
3. $\dfrac{(s+10)(s+100)}{s+1}$
4. $\dfrac{s+100}{(s+1)(s+10)}$
5. none of the above

Bode Plot: dB

$$H(s) = \frac{10s}{(s+1)(s+10)}$$





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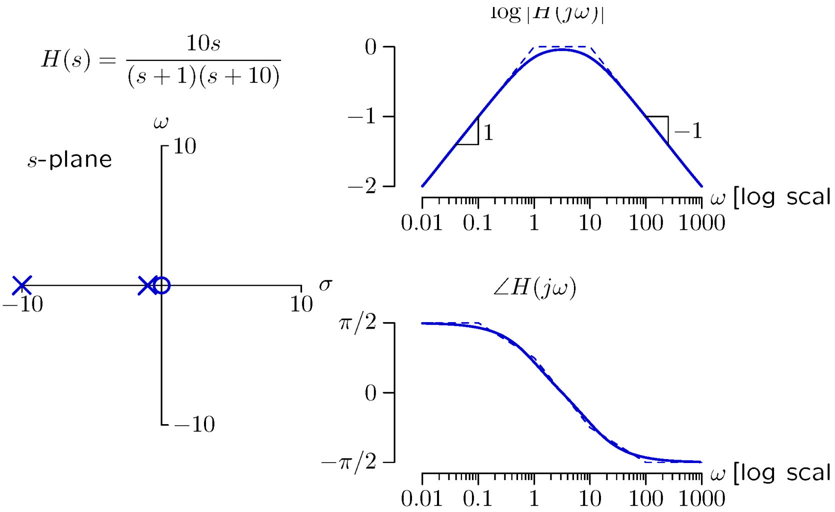

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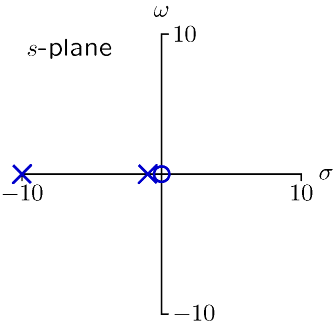
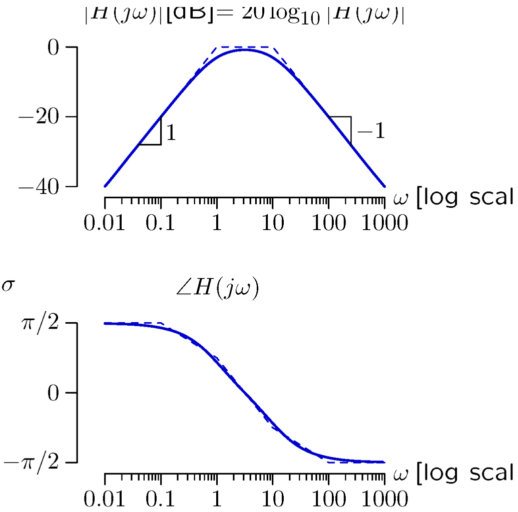
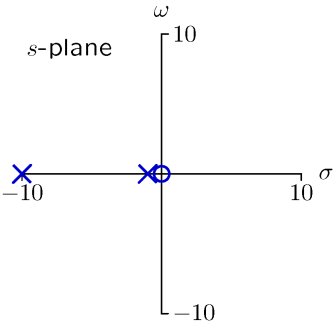
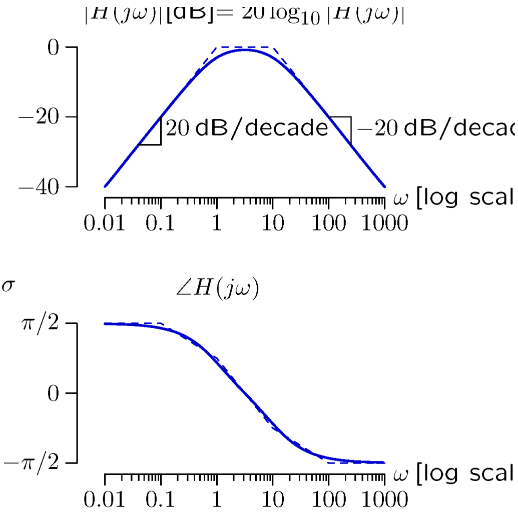




Bode Plot: dB

$$H(s) = \frac{10s}{(s+1)(s+10)}$$

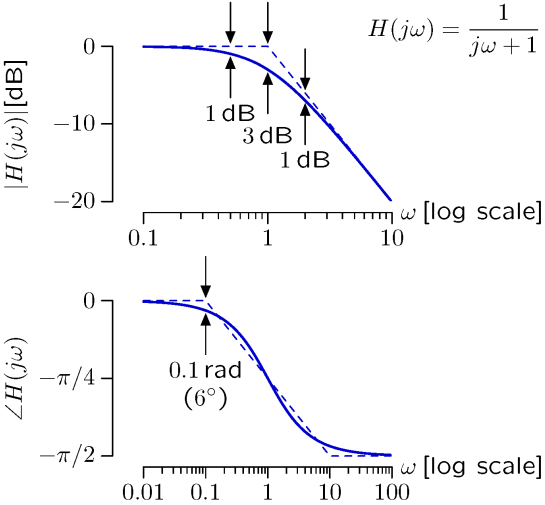




Bode Plot: Accuracy

The straight-line approximations are surprisingly accurate.

$$H(j\omega) = \frac{1}{j\omega + 1}$$

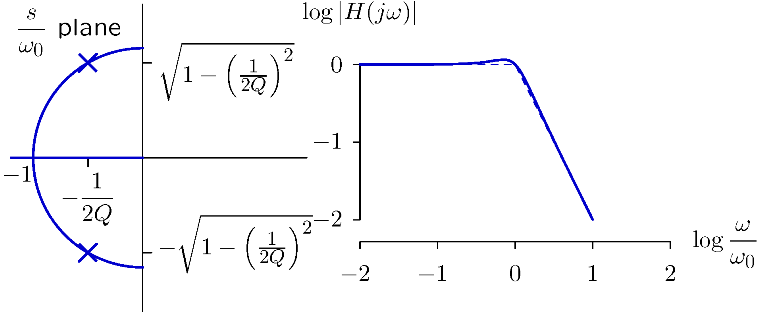


X	$20\log_{10} X$
1	0 dB
$\sqrt{2}$	≈ 3 dB
2	≈ 6 dB
10	20 dB
100	40 dB

Frequency Response of a High-Q System

The frequency-response magnitude of a high-Q system is peaked.

$$H(s)=\frac{1}{1+\frac{1}{Q}\frac{s}{\omega_0}+\left(\frac{s}{\omega_0}\right)^2}$$



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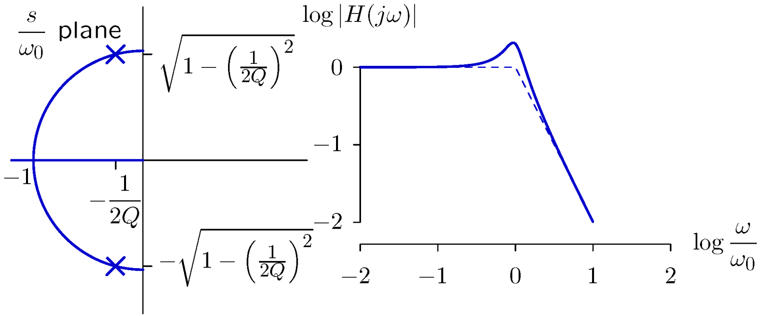

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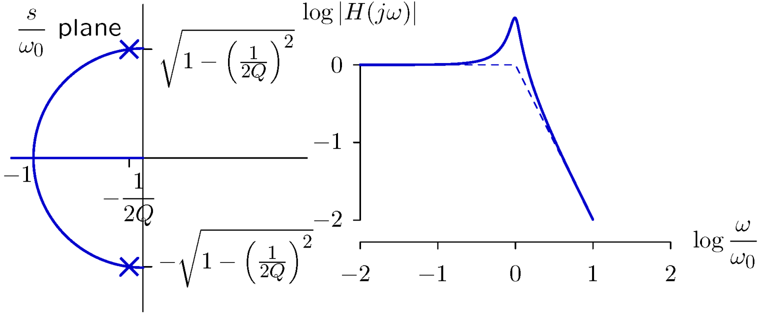

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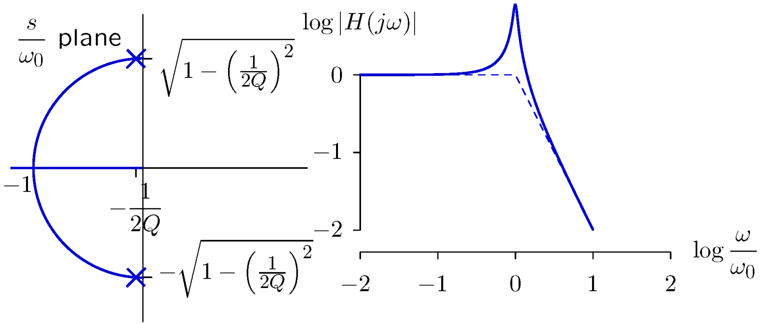

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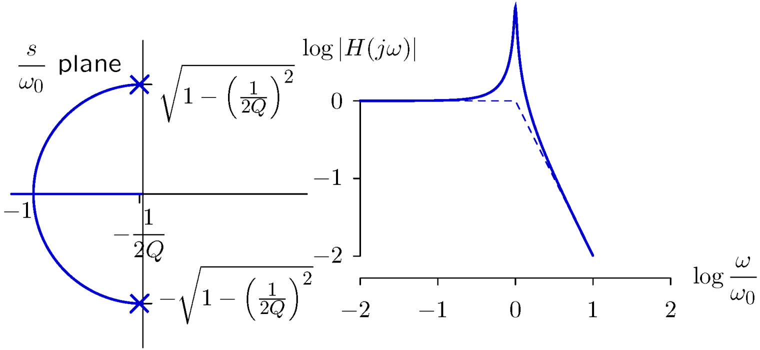
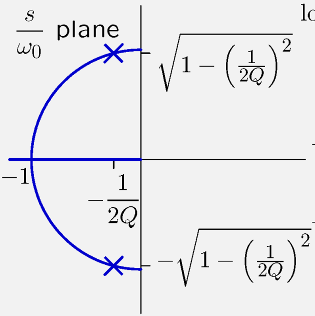
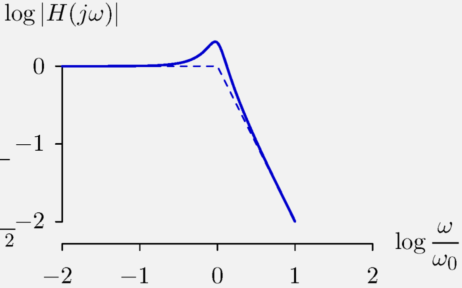


Check Yourself

Find dependence of peak magnitude on Q (assume $Q > 3$).

$$H(s) = \frac{1}{1 + \frac{1}{Q}\frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

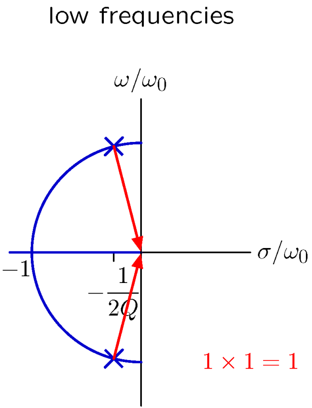




Check Yourself

Find dependence of peak magnitude on Q (assume $Q > 3$).

Analyze with vectors.

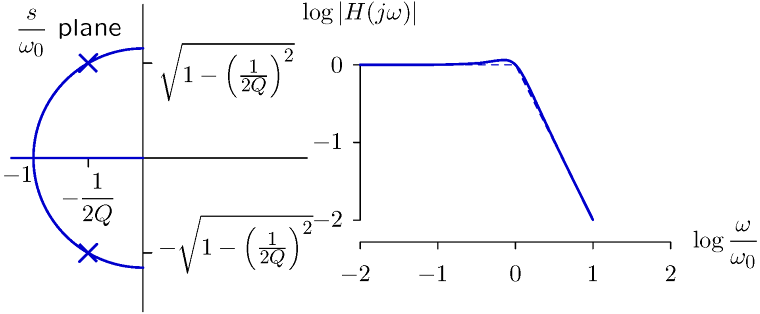


Peak magnitude increases with Q !

Frequency Response of a High-Q System

As Q increases, the width of the peak narrows.

$$H(s) = \frac{1}{1 + \frac{1}{Q}\frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$



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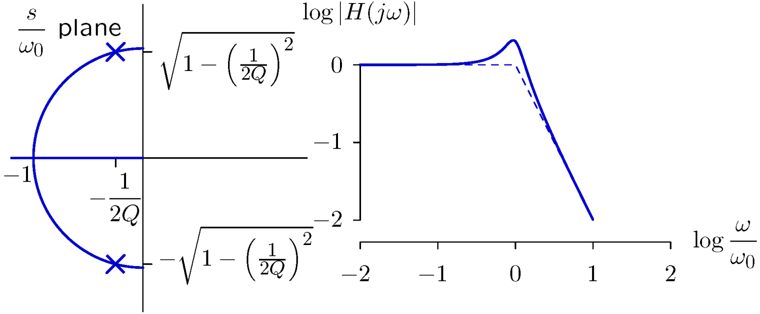

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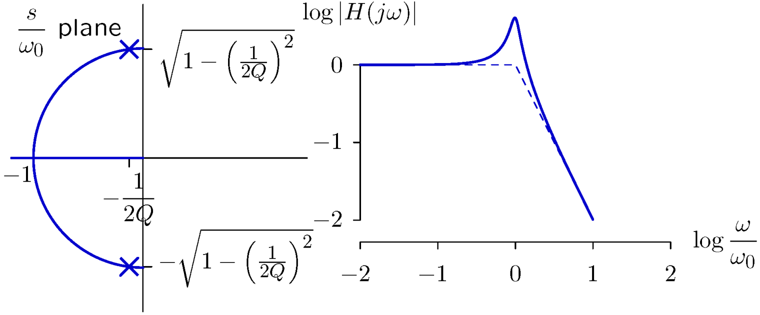

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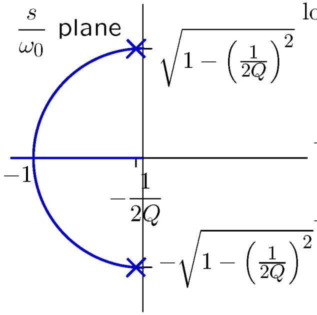

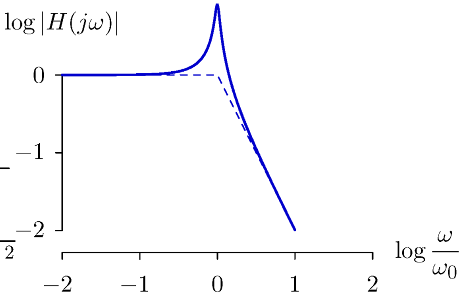

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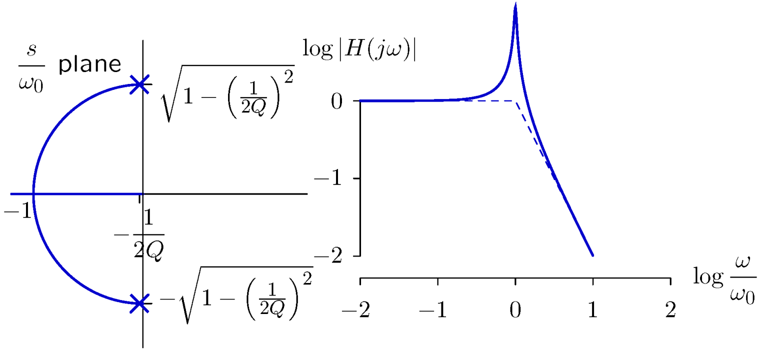
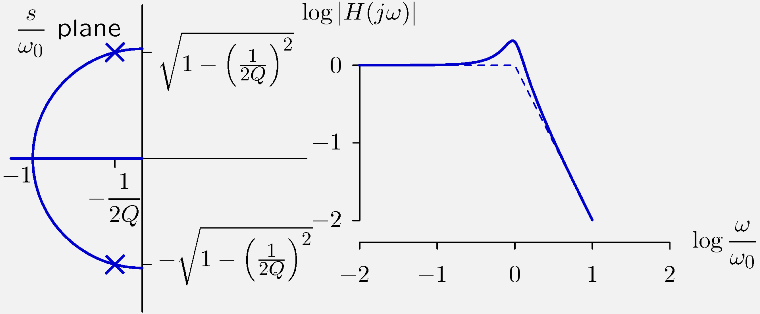


Check Yourself

Estimate the "3dB bandwidth" of the peak (assume $Q > 3$).

Let ω_l (or ω_h) represent the lowest (or highest) frequency for which the magnitude is greater than the peak value divided by $\sqrt{2}$. The 3dB bandwidth is then $\omega_h - \omega_l$.

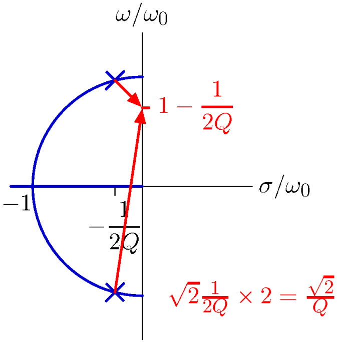


Check Yourself

Estimate the "3dB bandwidth" of the peak (assume $Q > 3$).

Analyze with vectors.

low frequencies | high frequencies

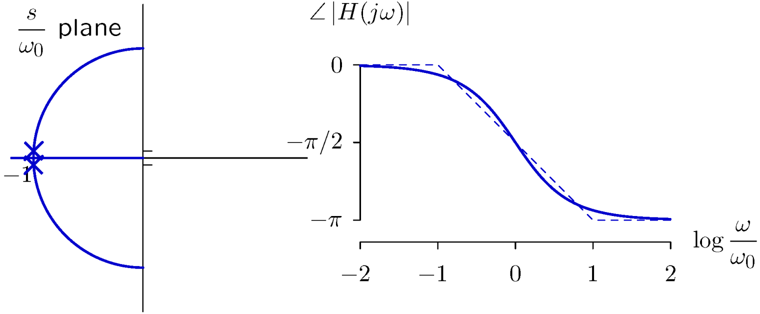


Bandwidth approximately $\frac{1}{Q}$

Frequency Response of a High-Q System

As Q increases, the phase changes more abruptly with ω.

$$H(s) = \frac{1}{1 + \frac{1}{Q}\frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$



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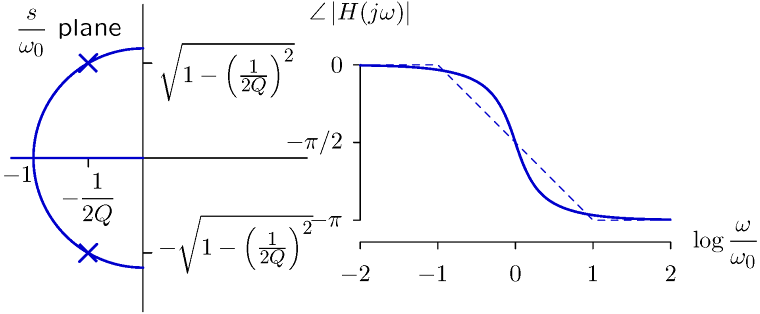

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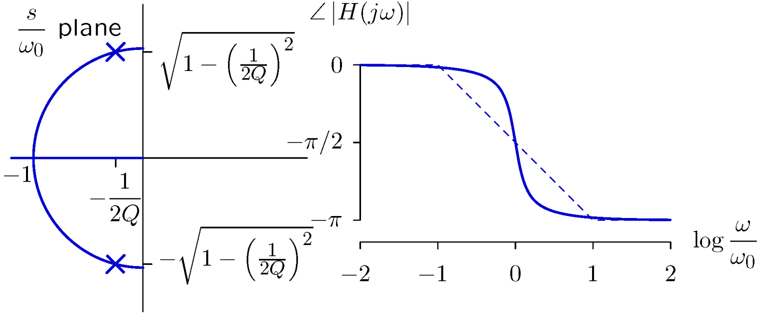

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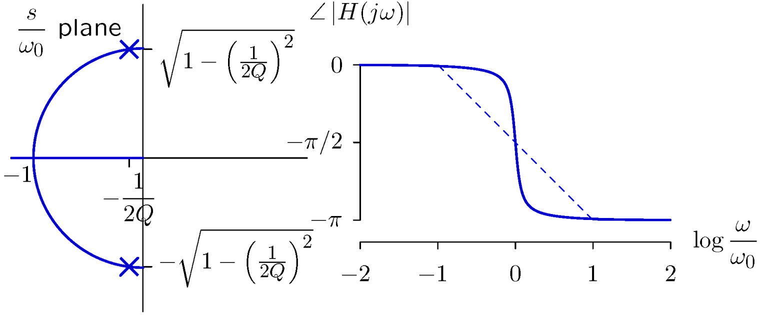

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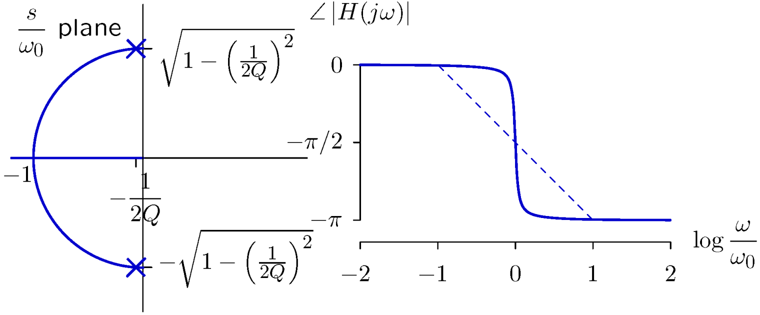
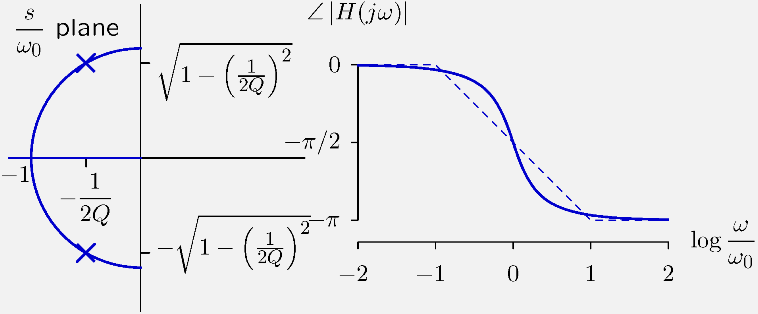


Check Yourself

Estimate change in phase that occurs over the 3dB bandwidth.

$$H(s) = \frac{1}{1 + \frac{1}{Q}\frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

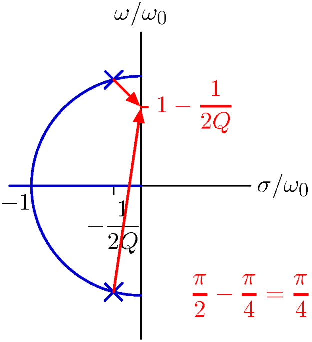


Check Yourself

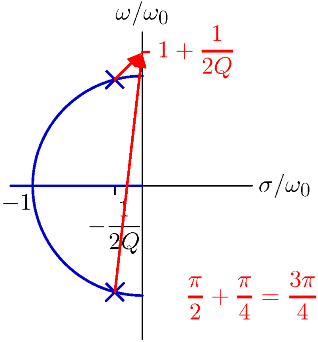
Estimate change in phase that occurs over the 3dB bandwidth.

Analyze with vectors.

low frequencies



high frequencies



Change in phase approximately $\frac{\pi}{2}$.

Summary

The frequency response of a system can be quickly determined using Bode plots.

Bode plots are constructed from sections that correspond to single poles and single zeros.

Responses for each section simply sum when plotted on logarithmic coordinates.

Assignments

- Reading Assignment: Chap. 9.4, 10.4, 3.8-3.11, 6.0-6.2, 6.5
- Homework 5