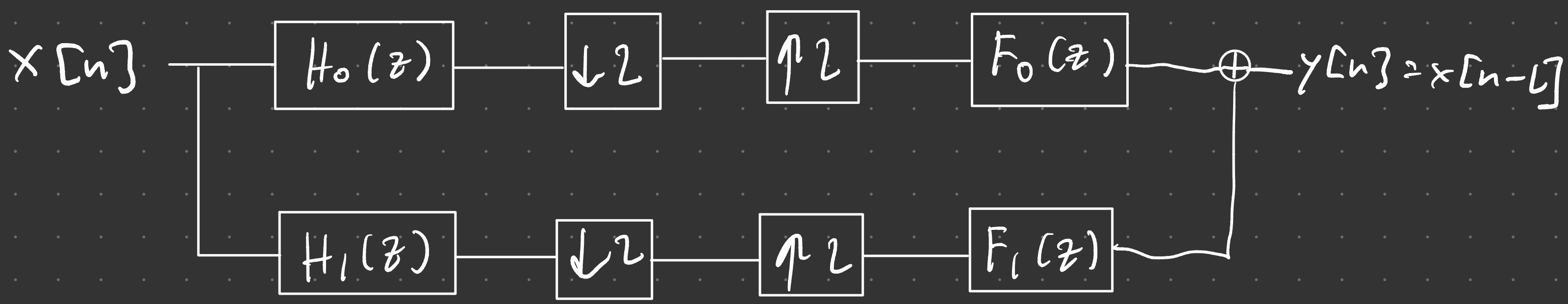
Last Time: Two-Channel PR Filter Banks



$$Y(z) = z^{-L} X(z)$$

$$= \frac{1}{2} X(z) \underbrace{\left[F_0(z) H_0(z) + F_1(z) H_1(z) \right]}_{\text{Distortion}}$$

$$+ \frac{1}{2} X(-z) \underbrace{\left[F_0(z) H_0(-z) + F_1(z) H_1(-z) \right]}_{\text{Aliasing}}$$

<u>PR Conditions (Vetterli, 1986)</u>

- $F_0(z) H_0(z) + F_1(z) H_1(z) = 2 z^{-L}$
- $F_0(z) H_0(-z) + F_1(z) H_1(-z) = 0$

Obs: The PR conditions are two equations with 4 unknowns (H_0, H_1, F_0, F_1).

$$\begin{bmatrix} H_0(z) & H_1(z) \\ H_0(-z) & H_1(-z) \end{bmatrix} \begin{bmatrix} F_0(z) \\ F_1(z) \end{bmatrix} = \begin{bmatrix} 2z^{-L} \\ 0 \end{bmatrix}$$

Given the analysis filters, we can find the synthesis filters by inverting this matrix.

Synthesis Filters

$$\begin{bmatrix} F_0(z) \\ F_1(z) \end{bmatrix} = \frac{2z^{-L}}{\Delta(z)} \begin{bmatrix} H_1(-z) & -H_1(z) \\ -H_0(-z) & H_0(z) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$= \frac{2z^{-L}}{\Delta(z)} \begin{bmatrix} H_1(-z) \\ -H_0(-z) \end{bmatrix}$$

Analysis Filters

$$\Delta(z) = H_0(z) H_1(-z) - H_0(-z) H_1(z)$$

Q: Suppose that H_0 & H_1 are FIR.

Are F_0 & F_1 FIR?

A: Not necessarily. The issue is $\Delta(z)$.

Might not even have causal or stable

IIR F_0 & F_1 ...

FIR PR Filter Bank Design

Q: How do we force F_0 & F_1 to be FIR?

A: Force $\Delta(z) = 2z^{-L} \Rightarrow$ FIR solⁿ.

could put
any gain
and delay

$$2z^{-L} = H_0(z)H_1(-z) - H_0(-z)H_1(z)$$

$$= \underbrace{H_0(z)F_0(z)}_{P_0(z)} - \underbrace{H_0(-z)F_0(-z)}_{P_0(-z)}$$

"product"

Design Procedure:

1. Find $P_0(z)$ that satisfies

$$P_0(z) - P_0(-z) = 2z^{-L}$$

How do we do this?

2. Factorize $P_0(z)$ into $H_0(z) \cdot F_0(z)$

3. Define $H_1(z) = F_0(-z)$

$$F_1(z) = -H_0(-z)$$

→ Different filter banks / wavelets / properties

$$P_0(z) = P_{0,even}(z^2) + z^{-1} P_{0,odd}(z^2)$$

$$-\quad P_0(-z) = P_{0,even}(z^2) - z^{-1} P_{0,odd}(z^2)$$

$$P_0(z) - P_0(-z) = \underbrace{2z^{-1}}_{\text{odd power}} \underbrace{P_{0,odd}(z^2)}_{\text{only even powers}} = 2z^{-L}$$

$$= 2z^{-(2k+1)}$$

$\Rightarrow L$ must be odd

$$P_{0,odd}(z^2) = z^{-2K} \Rightarrow P_{0,odd}(z) = z^{-K}$$

delay

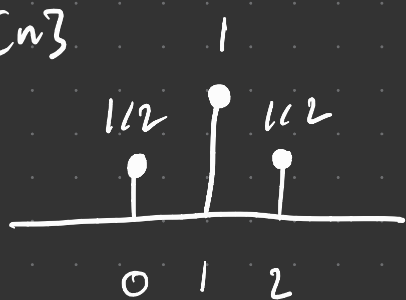
<u>Obs:</u> $P_{0,even}(z)$ is the design choice — even coeff.

$P_{0,odd}(z)$ <u>must</u> be a delay — odd coeff.

<u>Ex:</u> Let

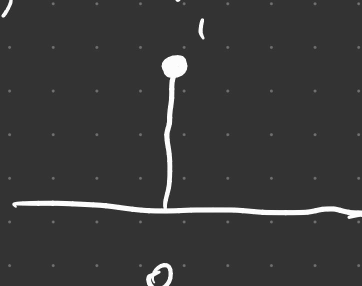
Is $p_0[n]$ valid? Yes

$p_0[n]$



$P_{0,even}[n]$

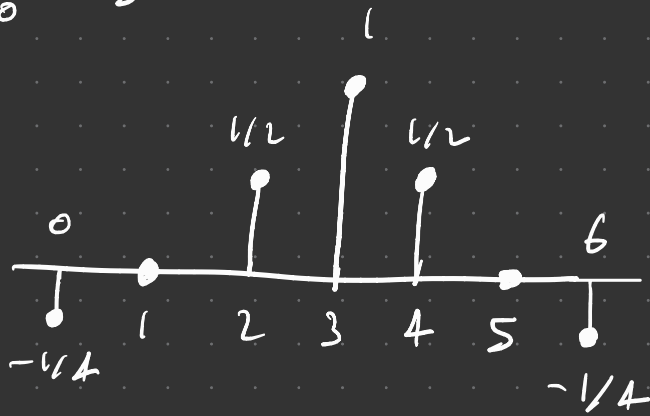
$P_{0,odd}[n] = \delta[n]$



$$K=0, \quad L=1$$

Ex: Let

$p_0[n]$

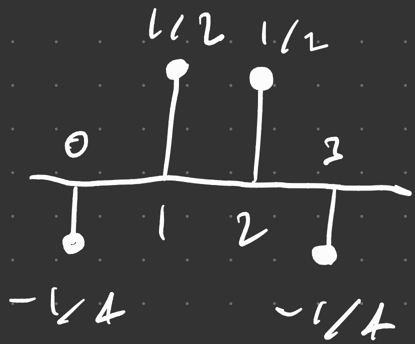


Is $p_0[n]$ valid?

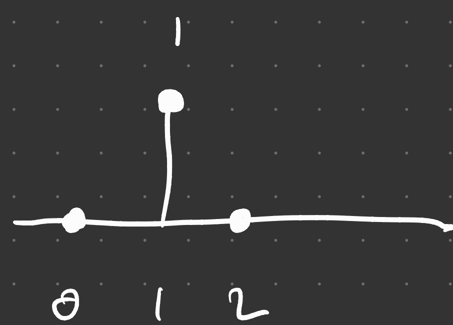
Yes

Type I Linear-Phase

$p_{0,even}[n]$



$p_{0,odd}[n] = \delta[n-1]$



$$k = 1, \; L = 3$$

Q: What kind of filter is this?

A: It is a (shifted) half-band filter:

$$p_0[2n - L] = \delta[n]$$

Def^{n}: A filter $p_0[n]$ of the form

$$p_0[2n-L] = \delta[n]$$

is called a <u>half-band filter centered at L</u>.

<u>Obs:</u> The length of the filter is $2L+1$.

<u>Obs:</u> We have now reduced the problem to designing half-band (interpolation) filters.

Half-Band Filter Design

If P_0 is a half-band filter centered at L, then

$$P_0(z) - P_0(-z) = 2z^{-L}$$

Q: What do people typically do?

A: Assume $P_0(z)$ is Type I Linear-Phase

Why not Type II? L is odd.

$$P_0(e^{j\omega}) = e^{-jL\omega} P_{ampl}(\omega)$$

real function

center of symmetry

$P(-z)$

$$P_0(e^{j(\omega-\pi)}) = e^{-jL(\omega-\pi)} P_{ampl}(\omega-\pi)$$

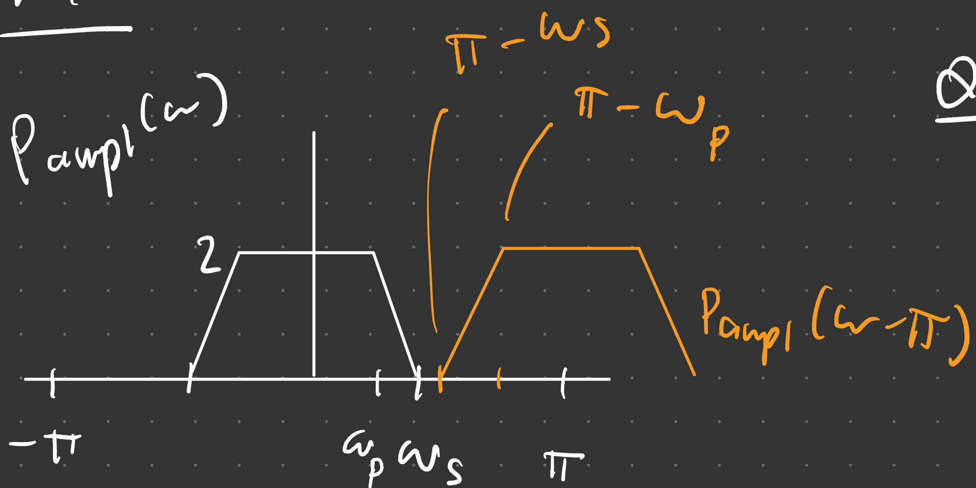
$$= e^{jL\pi} e^{-jL\omega} P_{ampl}(\omega-\pi)$$

$$= -e^{jL\omega} P_{ampl}(\omega-\pi)$$

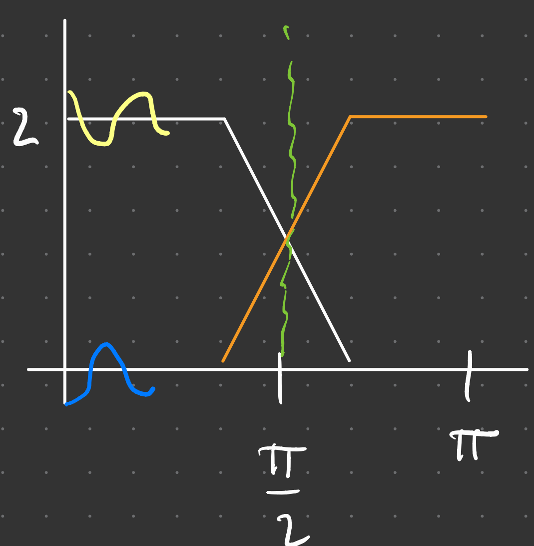
$$e^{-jL\omega} P_{ampl}(\omega) + e^{-jL\omega} P_{ampl}(\omega - \pi) = 2 e^{-jL\omega}$$

$$\boxed{P_{ampl}(\omega) + P_{ampl}(\omega - \pi) = 2}$$

Ex:



Q: How do we guarantee that these add to 2?



half-band

$$\pi - \omega_s = \omega_p$$

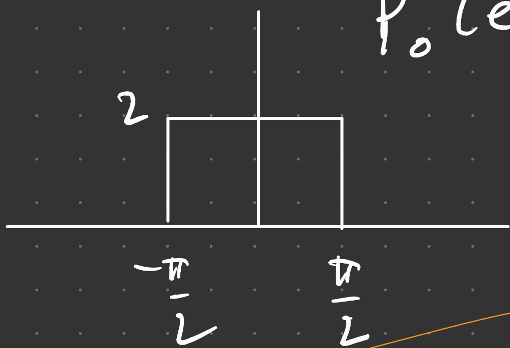
$$\omega_p + \omega_s = \pi$$

$$\boxed{\omega_s - \frac{\pi}{2} = \frac{\pi}{2} - \omega_p}$$

ripples need to cancel out

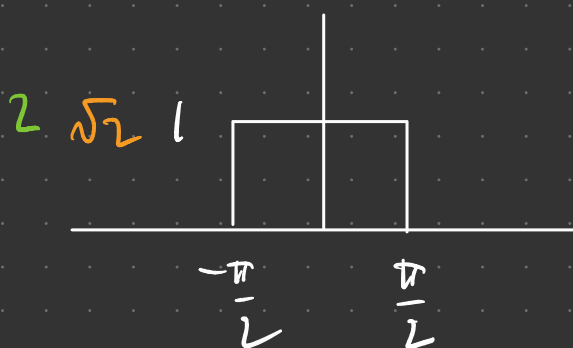
Ex: Ideal low-pass filter ($L=0$)

$$P_0(e^{j\omega}) = H_0(e^{j\omega})\,F_0(e^{j\omega})$$

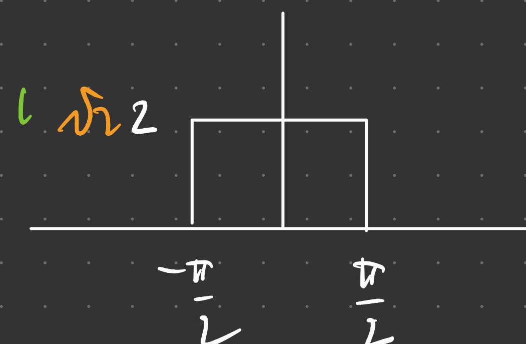


guarantee PR

$H_0(e^{j\omega})$



$F_0(e^{j\omega})$



Q: Why the gain factor of 2?

A: To account for the magnitude being halved from downsampling.

Remark: You will explore this in MATLAB in the homework.

Q: If P_0 is of length $2L+1$, how many coeffs do we have to design?

A: We only need to design $P_{0,even}$, which is itself symmetric.

L	# coeffs
1	1
3	2
5	3
7	4

$$\boxed{\frac{L+1}{2} \text{ coeffs}}$$

Q: What is $P_{0,even}$?

A: Type I Linear-Phase with Center of symmetry $\frac{L}{2}$.

$$P_{0,even}(e^{j\omega}) = e^{-j\frac{L}{2}\omega} P_{even,ampl}(\omega)$$

Putting everything together,

$$P_0(z) = P_{0,even}(z^2) + z^{-1} P_{0,odd}(z^2)$$

$$P_0(e^{j\omega}) = P_{0,even}(e^{j2\omega}) + e^{-jL\omega}$$

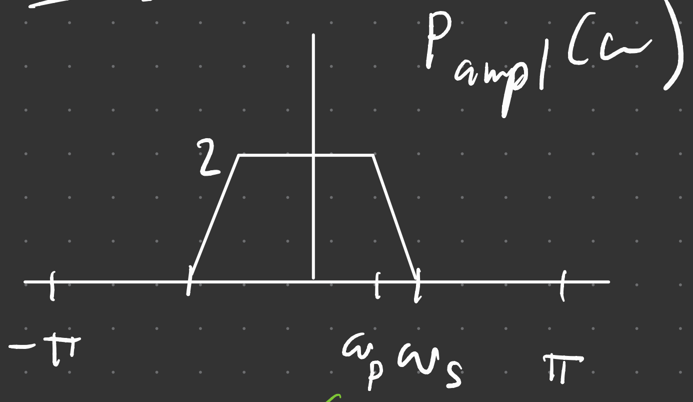
By ☆ and ☆,

$$e^{-jL\omega} P_{ampl}(\omega) = e^{-jL\omega} P_{even,ampl}(2\omega) + e^{-jL\omega}$$

$$P_{ampl}(\omega) = P_{even,ampl}(2\omega) + 1$$

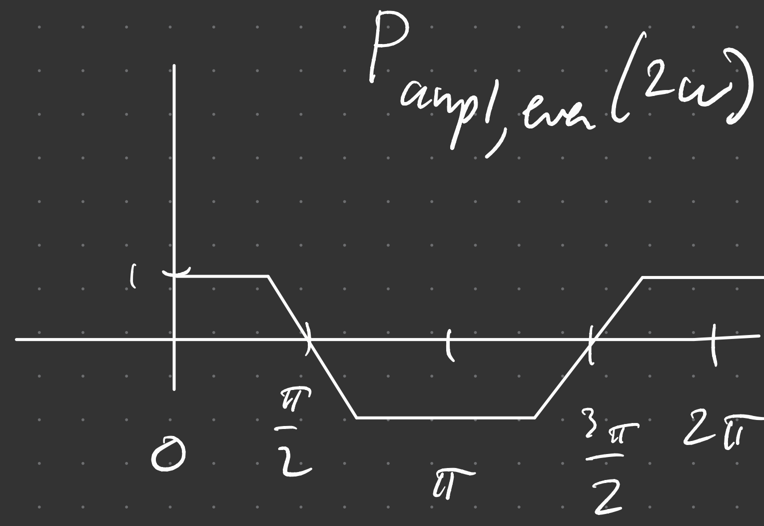
$$\boxed{P_{ampl}(\omega) - 1 = P_{even,ampl}(2\omega)}$$

Ex:



pass-band freq

stop-band freq

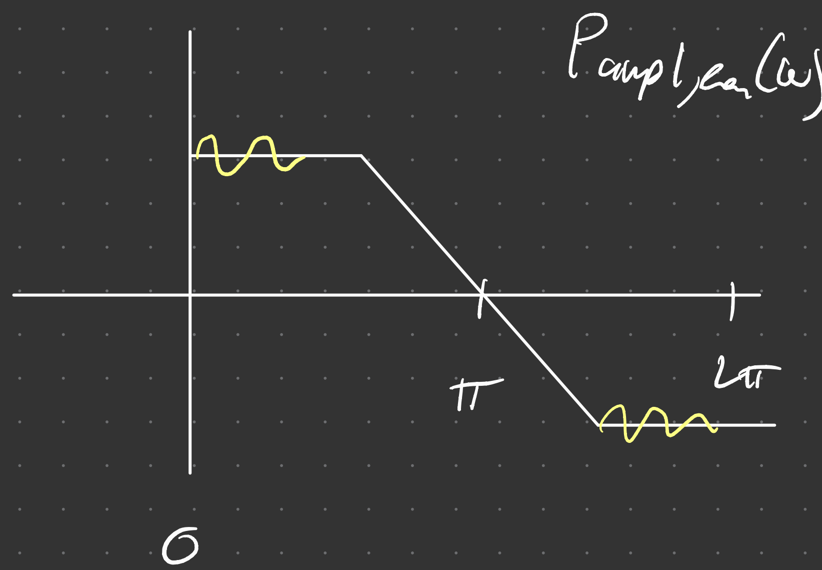


Type II

linear-phase

zero @ π

One band filter



ripples will automatically cancel by symmetry

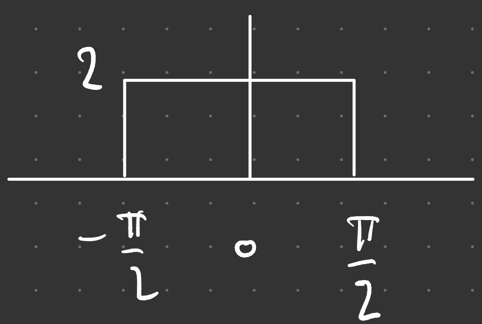
Remark: We've reduced the problem to designing a Type II linear-phase filter.

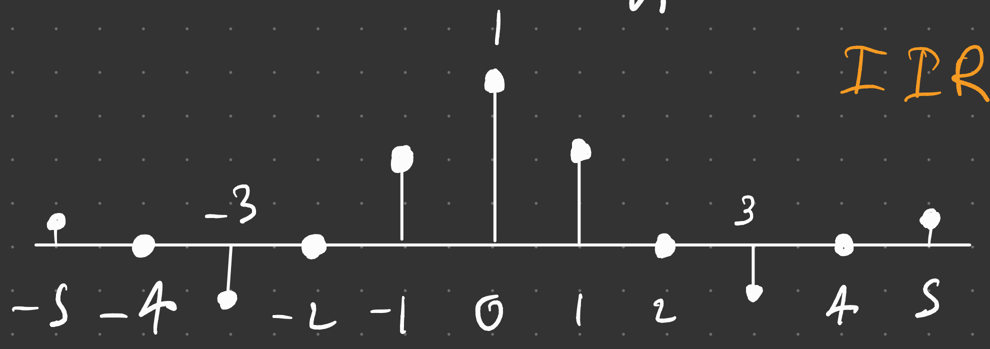
Window-Based Design Method

Goal: Approximate an ideal low-pass filter with an FIR filter.

$P_{ideal}(\omega)$

$$P_{ideal}[n] = 2\frac{\sin(\frac{\pi}{2}n)}{n}$$





$P_0[n] = P_{ideal}[n]\, w[n]$ 11-tap half-band filter

Remark: There's a whole industry in designing window functions.