

# HLS Lab B: FFT

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- Baseline FFT Code

FFT 主要可以分成三個 loop 完成，由外而內分別是: stages loop、butterfly loop、跟 point loop。Baseline 的 c-code 如下:

```
stages:for(stage=1; stage<= M; stage++)
{
    DFTpts = 1 << stage;          // DFT = 2^stage = po
    numBF = DFTpts/2;             // Butterfly WIDTHS in
    k=0;

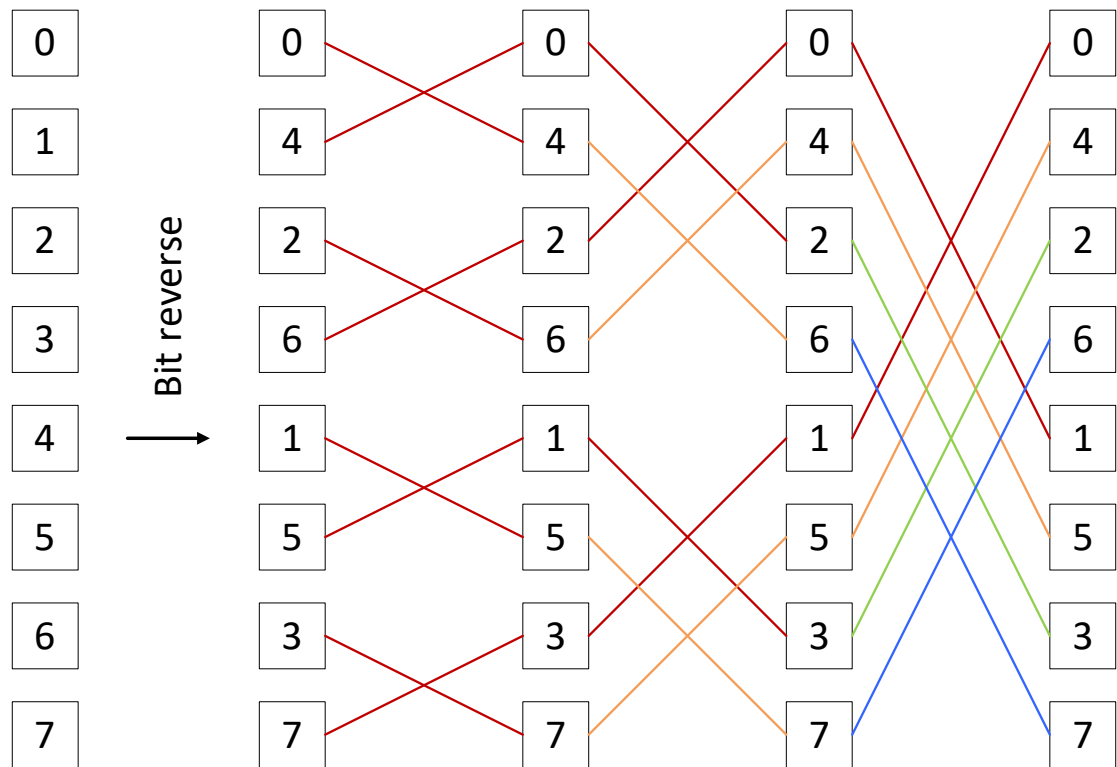
    e = -6.283185307178/DFTpts;

    a = 0.0;
    // Perform butterflies for j-th stage
    butterfly:for(j=0; j<numBF; j++)
    {
        c = cos(a);
        s = sin(a);
        a = a + e;

        // Compute butterflies that use same W**k
        DFTpts:for(i=j; i<SIZE; i += DFTpts)
        {
            i_lower = i + numBF;          //index of
            temp_R = X_R[i_lower]*c- X_I[i_lower]*s;
            temp_I = X_I[i_lower]*c+ X_R[i_lower]*s;

            X_R[i_lower] = X_R[i] - temp_R;
            X_I[i_lower] = X_I[i] - temp_I;
            X_R[i] = X_R[i] + temp_R;
            X_I[i] = X_I[i] + temp_I;
        }
        k+=step;
    }
    step=step/2;
}
```

其流程圖(以 8-points FFT 為例)為下



其中橫軸的方向對應到的 stages loop，而不同顏色的 butterfly 結構代表使用不一樣的 twiddle factor。

## ● FFT Optimization

### 1. Create Perfect Loop

首先為了讓 butterfly loop、跟 point loop 能更有效率地進行，我們將 stages loop 展開，並將 butterfly loop 與 point loop 寫成 perfect loop 的形式

```

void fft(DTYPE X_R[SIZE], DTYPE X_I[SIZE], DTYPE OUT_R[SIZE], DTYPE OUT_I[SIZE])
{
    #pragma HLS INTERFACE mode=ap_ctrl_none port=return
    #pragma HLS INTERFACE mode=s_axilite port=OUT_R
    #pragma HLS INTERFACE mode=s_axilite port=OUT_I
    #pragma HLS INTERFACE mode=s_axilite port=X_I
    #pragma HLS INTERFACE mode=s_axilite port=X_R

    #pragma HLS DATAFLOW

    DTYPE Stage_R0[SIZE], Stage_I0[SIZE];
    DTYPE Stage_R1[SIZE], Stage_I1[SIZE];
    DTYPE Stage_R2[SIZE], Stage_I2[SIZE];
    DTYPE Stage_R3[SIZE], Stage_I3[SIZE];
    DTYPE Stage_R4[SIZE], Stage_I4[SIZE];
    DTYPE Stage_R5[SIZE], Stage_I5[SIZE];
    DTYPE Stage_R6[SIZE], Stage_I6[SIZE];
    DTYPE Stage_R7[SIZE], Stage_I7[SIZE];
    DTYPE Stage_R8[SIZE], Stage_I8[SIZE];
    DTYPE Stage_R9[SIZE], Stage_I9[SIZE];
    bit_reverse(X_R, X_I, Stage_R0, Stage_I0);
    fft_first(Stage_R0, Stage_I0, Stage_R1, Stage_I1);
    fft_stages(2, Stage_R1, Stage_I1, Stage_R2, Stage_I2);
    fft_stages(3, Stage_R2, Stage_I2, Stage_R3, Stage_I3);
    fft_stages(4, Stage_R3, Stage_I3, Stage_R4, Stage_I4);
    fft_stages(5, Stage_R4, Stage_I4, Stage_R5, Stage_I5);
    fft_stages(6, Stage_R5, Stage_I5, Stage_R6, Stage_I6);
    fft_stages(7, Stage_R6, Stage_I6, Stage_R7, Stage_I7);
    fft_stages(8, Stage_R7, Stage_I7, Stage_R8, Stage_I8);
    fft_stages(9, Stage_R8, Stage_I8, Stage_R9, Stage_I9);
    fft_last(Stage_R9, Stage_I9, OUT_R, OUT_I);
}

```

```

void fft_stages(int stage, DTYPE X_R[SIZE], DTYPE X_I[SIZE], DTYPE OUT_R[SIZE], DTYPE OUT_I[SIZE])
{
    //Write a code that computes any arbitrary stages of the FFT
    //int DFTpts;
    //int numBF;
    int i, j;
    int i_lower;
    DTYPE temp_R; //temporary storage complex variable
    DTYPE temp_I; //temporary storage complex variable

    int t, step_t;
    int idx_higher, idx_lower;
    DTYPE sin_t, cos_t;
    step_t = (SIZE >> stage);
    t = 0;
    int n1, n2;
    n1 = (1 << (stage-1)); // 2^(stage-1) = (2^stage)/2
    n2 = (SIZE >> stage); // SIZE/2^stage
    butterfly:for(j=0; j<n1; j++)
    {
        DFTpts:for(i=0; i<n2; i++)
        {
            #pragma HLS PIPELINE
            sin_t = SIN[j*step_t];
            cos_t = COS[j*step_t];
            idx_higher = j + 2*i*n1;
            idx_lower = idx_higher + n1;
            temp_R = X_R[idx_lower]*cos_t- X_I[idx_lower]*sin_t;
            temp_I = X_I[idx_lower]*cos_t+ X_R[idx_lower]*sin_t;
            OUT_R[idx_lower] = X_R[idx_higher] - temp_R;
            OUT_I[idx_lower] = X_I[idx_higher] - temp_I;
            OUT_R[idx_higher] = X_R[idx_higher] + temp_R;
            OUT_I[idx_higher] = X_I[idx_higher] + temp_I;
        }
    }
}

```

## 2. Lookup Table

為了減少 cos 與 sin 的計算量，我們利用 python 生成 lookup table 對 sin 和 cos 進行查表

```
const DTYPE SIN[] = {
    -0.000000, -0.006136, -0.012272, -0.018407, -0.024541, -0.030675, -0.036807, -0.042938, -0.049068, -0.055195,
    -0.061321, -0.067444, -0.073565, -0.079682, -0.085797, -0.091909, -0.098017, -0.104122, -0.110222, -0.116319,
    -0.122411, -0.128498, -0.134581, -0.140658, -0.146730, -0.152797, -0.158858, -0.164913, -0.170962, -0.177004,
    -0.183040, -0.189069, -0.195090, -0.201105, -0.207111, -0.213110, -0.219101, -0.225084, -0.231058, -0.237024,
    -0.242980, -0.248928, -0.254865, -0.260794, -0.266713, -0.272621, -0.278520, -0.284408, -0.290285, -0.296151,
    -0.302000, -0.307825, -0.313639, -0.319442, -0.325234, -0.331015, -0.336785, -0.342544, -0.348292, -0.354029,
    -0.359755, -0.365470, -0.371174, -0.376867, -0.382549, -0.388219, -0.393878, -0.399526, -0.405163, -0.410789,
    -0.416404, -0.422008, -0.427601, -0.433183, -0.438754, -0.444314, -0.449863, -0.455401, -0.460928, -0.466444,
    -0.471949, -0.477443, -0.482926, -0.488398, -0.493859, -0.499309, -0.504748, -0.510176, -0.515593, -0.521000,
    -0.526396, -0.531781, -0.537155, -0.542518, -0.547870, -0.553211, -0.558541, -0.563860, -0.569168, -0.574465,
    -0.579751, -0.585026, -0.590290, -0.595543, -0.600785, -0.606016, -0.611236, -0.616445, -0.621643, -0.626830,
    -0.631996, -0.637151, -0.642295, -0.647428, -0.652550, -0.657661, -0.662761, -0.667850, -0.672928, -0.677995,
    -0.683051, -0.688097, -0.693132, -0.698156, -0.703169, -0.708171, -0.713162, -0.718142, -0.723111, -0.728069,
    -0.733016, -0.737952, -0.742877, -0.747791, -0.752694, -0.757586, -0.762467, -0.767337, -0.772196, -0.777044,
    -0.781881, -0.786707, -0.791522, -0.796326, -0.801119, -0.805901, -0.810672, -0.815433, -0.820183, -0.824923,
    -0.829652, -0.834371, -0.839080, -0.843778, -0.848465, -0.853141, -0.857806, -0.862460, -0.867104, -0.871737,
    -0.876360, -0.880972, -0.885574, -0.890165, -0.894745, -0.899314, -0.903873, -0.908421, -0.912959, -0.917486,
    -0.921993, -0.926480, -0.930947, -0.935394, -0.939821, -0.944228, -0.948615, -0.952982, -0.957329, -0.961656,
    -0.965963, -0.970250, -0.974517, -0.978764, -0.982991, -0.987198, -0.991385, -0.995552, -0.999699, -1.000000,
    1.000000, 0.999981, 0.999925, 0.999831, 0.999699, 0.999529, 0.999322, 0.999078, 0.998795, 0.998476,
    0.998118, 0.997723, 0.997290, 0.996820, 0.996313, 0.995767, 0.995185, 0.994565, 0.993907, 0.993212,
    0.992480, 0.991710, 0.990903, 0.990058, 0.989177, 0.988258, 0.987301, 0.986308, 0.985278, 0.984210,
    0.983105, 0.981964, 0.980785, 0.979570, 0.978317, 0.977038, 0.975733, 0.974403, 0.973048, 0.971669,
    0.970266, 0.968839, 0.967388, 0.965913, 0.964415, 0.962894, 0.961350, 0.959784, 0.958196, 0.956586,
    0.954954, 0.953300, 0.951625, 0.949929, 0.948212, 0.946474, 0.944715, 0.942936, 0.941136, 0.939315,
    0.937473, 0.935610, 0.933726, 0.931821, 0.929895, 0.927948, 0.925980, 0.923991, 0.921981, 0.919950,
    0.917898, 0.915825, 0.913731, 0.911616, 0.909480, 0.907323, 0.905145, 0.902946, 0.900726, 0.898485,
    0.896223, 0.893940, 0.891636, 0.889311, 0.886965, 0.884598, 0.882210, 0.879801, 0.877371, 0.874920,
    0.872448, 0.870000, 0.867525, 0.865023, 0.862505, 0.860000, 0.857467, 0.854917, 0.852350, 0.849757,
    0.847138, 0.844493, 0.841832, 0.839155, 0.836462, 0.833753, 0.831028, 0.828287, 0.825530, 0.822757,
    0.820000, 0.817168, 0.814361, 0.811538, 0.808699, 0.805844, 0.802973, 0.800087, 0.797186, 0.794270,
    0.791338, 0.788390, 0.785426, 0.782446, 0.779450, 0.776438, 0.773411, 0.770369, 0.767312, 0.764240,
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    0.149196, 0.143603, 0.138000, 0.132377, 0.126734, 0.121071, 0.115388, 0.109685, 0.103962, 0.098219,
    0.092456, 0.086673, 0.080870, 0.075047, 0.069204, 0.063341, 0.057458, 0.051545, 0.045602, 0.039629,
    0.033626, 0.027603, 0.021560, 0.015497, 0.009414, 0.003311, -0.002812, -0.008955, -0.015128,
    -0.021331, -0.027564, -0.033827, -0.040120, -0.046443, -0.052796, -0.059179, -0.065592, -0.072035,
    -0.078508, -0.084911, -0.091344, -0.097807, -0.104290, -0.110793, -0.117316, -0.123859, -0.130422,
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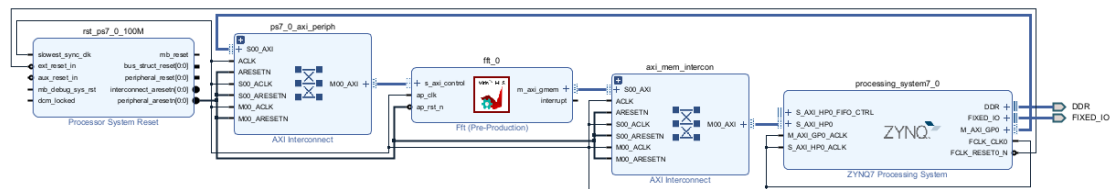
+ Detail:

\* Instance:

Instance	Module	Latency (cycles)		Latency (absolute)		Interval		Pipeline Type
		min	max	min	max	min	max	
entry_proc_U0	entry_proc	0	0	0 ns	0 ns	0	0	no
bit_reverse_U0	bit_reverse	2058	2058	20.580 us	20.580 us	2058	2058	no
fft_first_U0	fft_first	520	520	5.200 us	5.200 us	520	520	no
fft_stages_1_U0	fft_stages_1	530	530	5.300 us	5.300 us	530	530	no
fft_stages_2_U0	fft_stages_2	530	530	5.300 us	5.300 us	530	530	no
fft_stages_3_U0	fft_stages_3	530	530	5.300 us	5.300 us	530	530	no
fft_stages_4_U0	fft_stages_4	530	530	5.300 us	5.300 us	530	530	no
fft_stages_5_U0	fft_stages_5	530	530	5.300 us	5.300 us	530	530	no
fft_stages_6_U0	fft_stages_6	530	530	5.300 us	5.300 us	530	530	no
fft_stages_7_U0	fft_stages_7	530	530	5.300 us	5.300 us	530	530	no
fft_stages_U0	fft_stages	530	530	5.300 us	5.300 us	530	530	no
fft_last_U0	fft_last	2074	2074	20.740 us	20.740 us	2074	2074	no

## ● System Architecture

我們仿照 Lab2 的方式利用 AXI 介面將 HLS 的 IP 接上 ZYNQ7



## ● PYNQ Verification:

我們將結果放到 PYNQ 上做測試，並得到正確結果

Real Part RMSE: 1.7840247029189356e-05 Imaginary Part RMSE: 1.3904950782005702e-05  
PASS

