原 # x264源代码简单分析：编码器主干部分-2

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H.264源代码分析文章列表：

【编码 - x264】

【解码 - libavcodec H.264 解码器】

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本文继续记录x264编码器主干部分的源代码。上一篇文章记录x264_encoder_open()，x264_encoder_headers()，和x264_encoder_close()这三个函数，本文记录x264_encoder_encode()函数。

函数调用关系图

X264编码器主干部分的源代码在整个x264中的位置如下图所示。

单击查看更清晰的图片

X264编码器主干部分的函数调用关系如下图所示。

单击查看更清晰的图片

从图中可以看出，x264主干部分最复杂的函数就是x264_encoder_encode()，该函数完成了编码一帧YUV为H.264码流的工作。与之配合的还有打开编码器的函数x264_encoder_open()，关闭编码器的函数x264_encoder_close()，以及输出SPS/PPS/SEI这样的头信息的x264_encoder_headers()。

x264_encoder_open()用于打开编码器，其中初始化了libx264编码所需要的各种变量。它调用了下面的函数：

x264_validate_parameters()：检查输入参数（例如输入图像的宽高是否为正数）。
x264_predict_16x16_init()：初始化Intra16x16帧内预测汇编函数。
x264_predict_4x4_init()：初始化Intra4x4帧内预测汇编函数。
x264_pixel_init()：初始化像素值计算相关的汇编函数（包括SAD、SATD、SSD等）。
x264_dct_init()：初始化DCT变换和DCT反变换相关的汇编函数。
x264_mc_init()：初始化运动补偿相关的汇编函数。
x264_quant_init()：初始化量化和反量化相关的汇编函数。
x264_deblock_init()：初始化去块效应滤波器相关的汇编函数。
x264_lookahead_init()：初始化Lookahead相关的变量。
x264_ratecontrol_new()：初始化码率控制相关的变量。

x264_encoder_headers()输出SPS/PPS/SEI这些H.264码流的头信息。它调用了下面的函数：

x264_sps_write()：输出SPS
x264_pps_write()：输出PPS
x264_sei_version_write()：输出SEI

x264_encoder_encode()编码一帧YUV为H.264码流。它调用了下面的函数：

x264_frame_pop_unused()：获取1个x264_frame_t类型结构体fenc。如果frames.unused[]队列不为空，就调用x264_frame_pop()从unused[]队列取1个现成的；否则就调用x264_frame_new()创建一个新的。
x264_frame_copy_picture()：将输入的图像数据拷贝至fenc。
x264_lookahead_put_frame()：将fenc放入lookahead.next.list[]队列，等待确定帧类型。
x264_lookahead_get_frames()：通过lookahead分析帧类型。该函数调用了x264_slicetype_decide()，x264_slicetype_analyse()和x264_slicetype_frame_cost()等函数。经过一些列分析之后，最终确定了帧类型信息，并且将帧放入frames.current[]队列。
x264_frame_shift()：从frames.current[]队列取出1帧用于编码。
x264_reference_update()：更新参考帧队列。
x264_reference_reset()：如果为IDR帧，调用该函数清空参考帧列表。
x264_reference_hierarchy_reset()：如果是非IDR的I帧、P帧、B帧（可做为参考帧），调用该函数。
x264_reference_build_list()：创建参考帧列表list0和list1。
x264_ratecontrol_start()：开启码率控制。
x264_slice_init()：创建 Slice Header。
x264_slices_write()：编码数据（最关键的步骤）。其中调用了x264_slice_write()完成了编码的工作（注意“x264_slices_write()”和“x264_slice_write()”名字差了一个“s”）。
x264_encoder_frame_end()：编码结束后做一些后续处理，例如记录一些统计信息。其中调用了x264_encoder_encapsulate_nals()封装NALU（添加起始码），调用x264_frame_push_unused()将fenc重新放回frames.unused[]队列，并且调用x264_ratecontrol_end()结束码率控制。

x264_encoder_close()用于关闭解码器，其中释放了libx264初始化的时候使用的各种变量。它调用了下面的函数：

x264_lookahead_delete()：释放Lookahead相关的变量。
x264_ratecontrol_summary()：汇总码率控制信息。
x264_ratecontrol_delete()：关闭码率控制。

上一篇文章已经记录了x264_encoder_open()，x264_encoder_headers()，和x264_encoder_close()这三个函数的源代码。本文继续上一篇文章的内容，记录x264_encoder_encode()函数的源代码。

x264_encoder_encode()

x264_encoder_encode()是libx264的API函数，用于编码一帧YUV为H.264码流。该函数的声明如下所示。

[cpp]

```cpp
/* x264_encoder_encode:
 *      encode one picture.
 *      *pi_nal is the number of NAL units outputted in pp_nal.
 *      returns the number of bytes in the returned NALs.
 *      returns negative on error and zero if no NAL units returned.
 *      the payloads of all output NALs are guaranteed to be sequential in memory. */
int     x264_encoder_encode( x264_t *, x264_nal_t **pp_nal, int *pi_nal, x264_picture_t *pic_in, x264_picture_t *pic_out );
```

x264_encoder_encode()的定义如下所示。

[cpp]

```cpp
/****************************************************************************
 * x264_encoder_encode:
 *  XXX: i_poc   : is the poc of the current given picture
 *       i_frame : is the number of the frame being coded
 *  ex:  type frame poc
 *       I      0   2*0
 *       P      1   2*3
 *       B      2   2*1
 *       B      3   2*2
 *       P      4   2*6
 *       B      5   2*4
 *       B      6   2*5
 *
 * 注释和处理：雷霄骅
 * http://blog.csdn.net/leixiaohua1020
 * leixiaohua1020@126.com
 ****************************************************************************/
//编码一帧数据
int     x264_encoder_encode( x264_t *h,
                             x264_nal_t **pp_nal, int *pi_nal,
                             x264_picture_t *pic_in,
                             x264_picture_t *pic_out )
{
    x264_t *thread_current, *thread_prev, *thread_oldest;
    int i_nal_type, i_nal_ref_idc, i_global_qp;
    int overhead = NALU_OVERHEAD;

#if HAVE_OPENCL
    if( h->opencl.b_fatal_error )
        return -1;
#endif

    if( h->i_thread_frames > 1 )
    {
        thread_prev    = h->thread[ h->i_thread_phase ];
        h->i_thread_phase = (h->i_thread_phase + 1) % h->i_thread_frames;
        thread_current = h->thread[ h->i_thread_phase ];
        thread_oldest  = h->thread[ (h->i_thread_phase + 1) % h->i_thread_frames ];
        x264_thread_sync_context( thread_current, thread_prev );
        x264_thread_sync_ratecontrol( thread_current, thread_prev, thread_oldest );
        h = thread_current;
    }
    else
    {
        thread_current =
        thread_oldest  = h;
    }
    h->i_cpb_delay_pir_offset = h->i_cpb_delay_pir_offset_next;

    /* no data out */
    *pi_nal = 0;
    *pp_nal = NULL;

    /* ------------------- Setup new frame from picture -------------------- */
    if( pic_in != NULL )
    {
        /* 1: Copy the picture to a frame and move it to a buffer */
        //步骤1
        //fenc存储了编码帧
        //获取一帧的空间fenc，用来存放待编码的帧
        x264_frame_t *fenc = x264_frame_pop_unused( h, 0 );
        if( !fenc )
            return -1;

        //外部像素数据传递到内部系统
        //pic_in（外部结构体x264_picture_t）到fenc（内部结构体x264_frame_t）
        if( x264_frame_copy_picture( h, fenc, pic_in ) < 0 )
            return -1;
        //宽和高都确保是16的整数倍（宏块宽度的整数倍）
        if( h->param.i_width != 16 * h->mb.i_mb_width ||
            h->param.i_height != 16 * h->mb.i_mb_height )
            x264_frame_expand_border_mod16( h, fenc );//扩展至16整数倍

        fenc->i_frame = h->frames.i_input++;
```

```
        if( fenc->i_frame == 0 )
            h->frames.i_first_pts = fenc->i_pts;
        if( h->frames.i_bframe_delay && fenc->i_frame == h->frames.i_bframe_delay )
            h->frames.i_bframe_delay_time = fenc->i_pts - h->frames.i_first_pts;

        if( h->param.b_vfr_input && fenc->i_pts <= h->frames.i_largest_pts )
            x264_log( h, X264_LOG_WARNING, "non-strictly-monotonic PTS\n" );

        h->frames.i_second_largest_pts = h->frames.i_largest_pts;
        h->frames.i_largest_pts = fenc->i_pts;

        if( (fenc->i_pic_struct < PIC_STRUCT_AUTO) || (fenc->i_pic_struct > PIC_STRUCT_TRIPLE) )
            fenc->i_pic_struct = PIC_STRUCT_AUTO;

        if( fenc->i_pic_struct == PIC_STRUCT_AUTO )
        {
#if HAVE_INTERLACED
            int b_interlaced = fenc->param ? fenc->param->b_interlaced : h->param.b_interlaced;
#else
            int b_interlaced = 0;
#endif
            if( b_interlaced )
            {
                int b_tff = fenc->param ? fenc->param->b_tff : h->param.b_tff;
                fenc->i_pic_struct = b_tff ? PIC_STRUCT_TOP_BOTTOM : PIC_STRUCT_BOTTOM_TOP;
            }
            else
                fenc->i_pic_struct = PIC_STRUCT_PROGRESSIVE;
        }

        if( h->param.rc.b_mb_tree && h->param.rc.b_stat_read )
        {
            if( x264_macroblock_tree_read( h, fenc, pic_in->prop.quant_offsets ) )
                return -1;
        }
        else
            x264_stack_align( x264_adaptive_quant_frame, h, fenc, pic_in->prop.quant_offsets );

        if( pic_in->prop.quant_offsets_free )
            pic_in->prop.quant_offsets_free( pic_in->prop.quant_offsets );
        //降低分辨率处理（原来的一半），线性内插
        //注意这里并不是6抽头滤波器的半像素内插
        if( h->frames.b_have_lowres )
            x264_frame_init_lowres( h, fenc );

        /* 2: Place the frame into the queue for its slice type decision */
        //步骤2
        //fenc放入lookahead.next.list[]队列，等待确定帧类型
        x264_lookahead_put_frame( h, fenc );

        if( h->frames.i_input <= h->frames.i_delay + 1 - h->i_thread_frames )
        {
            /* Nothing yet to encode, waiting for filling of buffers */
            pic_out->i_type = X264_TYPE_AUTO;
            return 0;
        }
    }
    else
    {
        //输入数据为空的时候（Flush Encoder？），不需要lookahead

        /* signal kills for lookahead thread */
        x264_pthread_mutex_lock( &h->lookahead->ifbuf.mutex );
        h->lookahead->b_exit_thread = 1;
        x264_pthread_cond_broadcast( &h->lookahead->ifbuf.cv_fill );
        x264_pthread_mutex_unlock( &h->lookahead->ifbuf.mutex );
    }

    h->i_frame++;
    /* 3: The picture is analyzed in the lookahead */
    // 步骤3
    //通过lookahead分析帧类型
    if( !h->frames.current[0] )
        x264_lookahead_get_frames( h );

    if( !h->frames.current[0] && x264_lookahead_is_empty( h ) )
        return x264_encoder_frame_end( thread_oldest, thread_current, pp_nal, pi_nal, pic_out );

    /* ------------------- Get frame to be encoded ------------------------- *
    /* 4: get picture to encode */
    //从frames.current[]队列取出1帧[0]用于编码
    h->fenc = x264_frame_shift( h->frames.current );

    /* If applicable, wait for previous frame reconstruction to finish */
    if( h->param.b_sliced_threads )
        if( x264_threadpool_wait_all( h ) < 0 )
            return -1;

    if( h->i_frame == h->i_thread_frames - 1 )
        h->i_reordered_pts_delay = h->fenc->i_reordered_pts;
    if( h->reconfig )
```

```
    if( h->reconfig )
    {
        x264_encoder_reconfig_apply( h, &h->reconfig_h->param );
        h->reconfig = 0;
    }
    if( h->fenc->param )
    {
        x264_encoder_reconfig_apply( h, h->fenc->param );
        if( h->fenc->param->param_free )
        {
            h->fenc->param->param_free( h->fenc->param );
            h->fenc->param = NULL;
        }
    }

    // ok to call this before encoding any frames, since the initial values of fdec have b_kept_as_ref=0
    //更新参考帧队列frames.reference[].若为B帧则不更新
    //重建帧fdec移植参考帧列表，新建一个fdec
    if( x264_reference_update( h ) )
        return -1;
    h->fdec->i_lines_completed = -1;

    if( !IS_X264_TYPE_I( h->fenc->i_type ) )
    {
        int valid_refs_left = 0;
        for( int i = 0; h->frames.reference[i]; i++ )
            if( !h->frames.reference[i]->b_corrupt )
                valid_refs_left++;
        /* No valid reference frames left: force an IDR. */
        if( !valid_refs_left )
        {
            h->fenc->b_keyframe = 1;
            h->fenc->i_type = X264_TYPE_IDR;
        }
    }

    if( h->fenc->b_keyframe )
    {
        h->frames.i_last_keyframe = h->fenc->i_frame;
        if( h->fenc->i_type == X264_TYPE_IDR )
        {
            h->i_frame_num = 0;
            h->frames.i_last_idr = h->fenc->i_frame;
        }
    }
    h->sh.i_mmco_command_count =
    h->sh.i_mmco_remove_from_end = 0;
    h->b_ref_reorder[0] =
    h->b_ref_reorder[1] = 0;
    h->fdec->i_poc =
    h->fenc->i_poc = 2 * ( h->fenc->i_frame - X264_MAX( h->frames.i_last_idr, 0 ) );

    /* ------------------- Setup frame context ----------------------------- *
    /* 5: Init data dependent of frame type */
    if( h->fenc->i_type == X264_TYPE_IDR )
    {
        //I与IDR区别
        //注意IDR会导致参考帧列清空，而I不会
        //I图像之后的图像可以引用I图像之间的图像做运动参考
        /* reset ref pictures */
        i_nal_type    = NAL_SLICE_IDR;
        i_nal_ref_idc = NAL_PRIORITY_HIGHEST;
        h->sh.i_type = SLICE_TYPE_I;
        //若是IDR帧，则清空所有参考帧
        x264_reference_reset( h );
        h->frames.i_poc_last_open_gop = -1;
    }
    else if( h->fenc->i_type == X264_TYPE_I )
    {
        //I与IDR区别
        //注意IDR会导致参考帧列清空，而I不会
        //I图像之后的图像可以引用I图像之间的图像做运动参考
        i_nal_type    = NAL_SLICE;
        i_nal_ref_idc = NAL_PRIORITY_HIGH; /* Not completely true but for now it is (as all I/P are kept as ref)*/
        h->sh.i_type = SLICE_TYPE_I;
        x264_reference_hierarchy_reset( h );
        if( h->param.b_open_gop )
            h->frames.i_poc_last_open_gop = h->fenc->b_keyframe ? h->fenc->i_poc : -1;
    }
    else if( h->fenc->i_type == X264_TYPE_P )
    {
        i_nal_type    = NAL_SLICE;
        i_nal_ref_idc = NAL_PRIORITY_HIGH; /* Not completely true but for now it is (as all I/P are kept as ref)*/
        h->sh.i_type = SLICE_TYPE_P;
        x264_reference_hierarchy_reset( h );
        h->frames.i_poc_last_open_gop = -1;
    }
    else if( h->fenc->i_type == X264_TYPE_BREF )
    {
        //可以作为参考帧的B帧，这是个特色

        i_nal_type    = NAL_SLICE;
```

```
        i_nal_ref_idc = h->param.i_bframe_pyramid == X264_B_PYRAMID_STRICT ? NAL_PRIORITY_LOW : NAL_PRIORITY_HIGH;
        h->sh.i_type = SLICE_TYPE_B;
        x264_reference_hierarchy_reset( h );
    }
    else    /* B frame */
    {
        //最普通

        i_nal_type    = NAL_SLICE;
        i_nal_ref_idc = NAL_PRIORITY_DISPOSABLE;
        h->sh.i_type = SLICE_TYPE_B;
    }
    //重建帧与编码帧的赋值...
    h->fdec->i_type = h->fenc->i_type;
    h->fdec->i_frame = h->fenc->i_frame;
    h->fenc->b_kept_as_ref =
    h->fdec->b_kept_as_ref = i_nal_ref_idc != NAL_PRIORITY_DISPOSABLE && h->param.i_keyint_max > 1;

    h->fdec->mb_info = h->fenc->mb_info;
    h->fdec->mb_info_free = h->fenc->mb_info_free;
    h->fenc->mb_info = NULL;
    h->fenc->mb_info_free = NULL;

    h->fdec->i_pts = h->fenc->i_pts;
    if( h->frames.i_bframe_delay )
    {
        int64_t *prev_reordered_pts = thread_current->frames.i_prev_reordered_pts;
        h->fdec->i_dts = h->i_frame > h->frames.i_bframe_delay
                       ? prev_reordered_pts[ (h->i_frame - h->frames.i_bframe_delay) % h->frames.i_bframe_delay ]
                       : h->fenc->i_reordered_pts - h->frames.i_bframe_delay_time;
        prev_reordered_pts[ h->i_frame % h->frames.i_bframe_delay ] = h->fenc->i_reordered_pts;
    }
    else
        h->fdec->i_dts = h->fenc->i_reordered_pts;
    if( h->fenc->i_type == X264_TYPE_IDR )
        h->i_last_idr_pts = h->fdec->i_pts;

    /* ------------------- Init                ----------------------------- */
    /* build ref list 0/1 */
    //创建参考帧列表list0和list1
    x264_reference_build_list( h, h->fdec->i_poc );

    /* ---------------------- Write the bitstream -------------------------- */
    /* Init bitstream context */
    //用于输出
    if( h->param.b_sliced_threads )
    {
        for( int i = 0; i < h->param.i_threads; i++ )
        {
            bs_init( &h->thread[i]->out.bs, h->thread[i]->out.p_bitstream, h->thread[i]->out.i_bitstream );
            h->thread[i]->out.i_nal = 0;
        }
    }
    else
    {
        bs_init( &h->out.bs, h->out.p_bitstream, h->out.i_bitstream );
        h->out.i_nal = 0;
    }

    if( h->param.b_aud )
    {
        int pic_type;

        if( h->sh.i_type == SLICE_TYPE_I )
            pic_type = 0;
        else if( h->sh.i_type == SLICE_TYPE_P )
            pic_type = 1;
        else if( h->sh.i_type == SLICE_TYPE_B )
            pic_type = 2;
        else
            pic_type = 7;

        x264_nal_start( h, NAL_AUD, NAL_PRIORITY_DISPOSABLE );
        bs_write( &h->out.bs, 3, pic_type );
        bs_rbsp_trailing( &h->out.bs );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + NALU_OVERHEAD;
    }

    h->i_nal_type = i_nal_type;
    h->i_nal_ref_idc = i_nal_ref_idc;

    if( h->param.b_intra_refresh )
    {
        if( IS_X264_TYPE_I( h->fenc->i_type ) )
        {
            h->fdec->i_frames_since_pir = 0;
            h->b_queued_intra_refresh = 0;
            /* PIR is currently only supported with ref == 1, so any intra frame effectively refreshes
             * the whole frame and counts as an intra refresh. */
```

```c
            h->fdec->f_pir_position = h->mb.i_mb_width;
        }
        else if( h->fenc->i_type == X264_TYPE_P )
        {
            int pocdiff = (h->fdec->i_poc - h->fref[0][0]->i_poc)/2;
            float increment = X264_MAX( ((float)h->mb.i_mb_width-1) / h->param.i_keyint_max, 1 );
            h->fdec->f_pir_position = h->fref[0][0]->f_pir_position;
            h->fdec->i_frames_since_pir = h->fref[0][0]->i_frames_since_pir + pocdiff;
            if( h->fdec->i_frames_since_pir >= h->param.i_keyint_max ||
                (h->b_queued_intra_refresh && h->fdec->f_pir_position + 0.5 >= h->mb.i_mb_width) )
            {
                h->fdec->f_pir_position = 0;
                h->fdec->i_frames_since_pir = 0;
                h->b_queued_intra_refresh = 0;
                h->fenc->b_keyframe = 1;
            }
            h->fdec->i_pir_start_col = h->fdec->f_pir_position+0.5;
            h->fdec->f_pir_position += increment * pocdiff;
            h->fdec->i_pir_end_col = h->fdec->f_pir_position+0.5;
            /* If our intra refresh has reached the right side of the frame, we're done. */
            if( h->fdec->i_pir_end_col >= h->mb.i_mb_width - 1 )
            {
                h->fdec->f_pir_position = h->mb.i_mb_width;
                h->fdec->i_pir_end_col = h->mb.i_mb_width - 1;
            }
        }
    }

    if( h->fenc->b_keyframe )
    {
        //每个关键帧前面重复加上SPS和PPS
        /* Write SPS and PPS */
        if( h->param.b_repeat_headers )
        {
            /* generate sequence parameters */
            x264_nal_start( h, NAL_SPS, NAL_PRIORITY_HIGHEST );
            x264_sps_write( &h->out.bs, h->sps );
            if( x264_nal_end( h ) )
                return -1;
            /* Pad AUD/SPS to 256 bytes like Panasonic */
            if( h->param.i_avcintra_class )
                h->out.nal[h->out.i_nal-1].i_padding = 256 - bs_pos( &h->out.bs ) / 8 - 2*NALU_OVERHEAD;
            overhead += h->out.nal[h->out.i_nal-1].i_payload + h->out.nal[h->out.i_nal-1].i_padding + NALU_OVERHEAD;

            /* generate picture parameters */
            x264_nal_start( h, NAL_PPS, NAL_PRIORITY_HIGHEST );
            x264_pps_write( &h->out.bs, h->sps, h->pps );
            if( x264_nal_end( h ) )
                return -1;
            if( h->param.i_avcintra_class )
                h->out.nal[h->out.i_nal-1].i_padding = 256 - h->out.nal[h->out.i_nal-1].i_payload - NALU_OVERHEAD;
            overhead += h->out.nal[h->out.i_nal-1].i_payload + h->out.nal[h->out.i_nal-1].i_padding + NALU_OVERHEAD;
        }

        /* when frame threading is used, buffering period sei is written in x264_encoder_frame_end */
        if( h->i_thread_frames == 1 && h->sps->vui.b_nal_hrd_parameters_present )
        {
            x264_hrd_fullness( h );
            x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
            x264_sei_buffering_period_write( h, &h->out.bs );
            if( x264_nal_end( h ) )
               return -1;
            overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
        }
    }

    /* write extra sei */
    //下面很大一段代码用于写入SEI（一部分是为了适配其他的解码器）==========================================
    for( int i = 0; i < h->fenc->extra_sei.num_payloads; i++ )
    {
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        x264_sei_write( &h->out.bs, h->fenc->extra_sei.payloads[i].payload, h->fenc->extra_sei.payloads[i].payload_size,
                        h->fenc->extra_sei.payloads[i].payload_type );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
        if( h->fenc->extra_sei.sei_free )
        {
            h->fenc->extra_sei.sei_free( h->fenc->extra_sei.payloads[i].payload );
            h->fenc->extra_sei.payloads[i].payload = NULL;
        }
    }

    if( h->fenc->extra_sei.sei_free )
    {
        h->fenc->extra_sei.sei_free( h->fenc->extra_sei.payloads );
        h->fenc->extra_sei.payloads = NULL;
        h->fenc->extra_sei.sei_free = NULL;
    }
    //特殊的SEI信息（Avid等解码器需要）
    if( h->fenc->b_keyframe )
```

```
    {
        /* Avid's decoder strictly wants two SEIs for AVC-Intra so we can't insert the x264 SEI */
        if( h->param.b_repeat_headers && h->fenc->i_frame == 0 && !h->param.i_avcintra_class )
        {
            /* identify ourself */
            x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
            if( x264_sei_version_write( h, &h->out.bs ) )
                return -1;
            if( x264_nal_end( h ) )
                return -1;
            overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
        }

        if( h->fenc->i_type != X264_TYPE_IDR )
        {
            int time_to_recovery = h->param.b_open_gop ? 0 : X264_MIN( h->mb.i_mb_width - 1, h->param.i_keyint_max ) + h->param.i_bframe - 1;
            x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
            x264_sei_recovery_point_write( h, &h->out.bs, time_to_recovery );
            if( x264_nal_end( h ) )
                return -1;
            overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
        }
    }

    if( h->param.i_frame_packing >= 0 && (h->fenc->b_keyframe || h->param.i_frame_packing == 5) )
    {
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        x264_sei_frame_packing_write( h, &h->out.bs );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
    }

    /* generate sei pic timing */
    if( h->sps->vui.b_pic_struct_present || h->sps->vui.b_nal_hrd_parameters_present )
    {
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        x264_sei_pic_timing_write( h, &h->out.bs );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
    }

    /* As required by Blu-ray. */
    if( !IS_X264_TYPE_B( h->fenc->i_type ) && h->b_sh_backup )
    {
        h->b_sh_backup = 0;
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        x264_sei_dec_ref_pic_marking_write( h, &h->out.bs );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;
    }

    if( h->fenc->b_keyframe && h->param.b_intra_refresh )
        h->i_cpb_delay_pir_offset_next = h->fenc->i_cpb_delay;

    /* Filler space: 10 or 18 SEIs' worth of space, depending on resolution */
    if( h->param.i_avcintra_class )
    {
        /* Write an empty filler NAL to mimic the AUD in the P2 format*/
        x264_nal_start( h, NAL_FILLER, NAL_PRIORITY_DISPOSABLE );
        x264_filler_write( h, &h->out.bs, 0 );
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + NALU_OVERHEAD;

        /* All lengths are magic lengths that decoders expect to see */
        /* "UMID" SEI */
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        if( x264_sei_avcintra_umid_write( h, &h->out.bs ) < 0 )
            return -1;
        if( x264_nal_end( h ) )
            return -1;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + SEI_OVERHEAD;

        int unpadded_len;
        int total_len;
        if( h->param.i_height == 1080 )
        {
            unpadded_len = 5780;
            total_len = 17*512;
        }
        else
        {
            unpadded_len = 2900;
            total_len = 9*512;
        }
        /* "VANC" SEI */
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
```

```
        if( x264_sei_avcintra_vanc_write( h, &h->out.bs, unpadded_len ) < 0 )
            return -1;
        if( x264_nal_end( h ) )
            return -1;

        h->out.nal[h->out.i_nal-1].i_padding = total_len - h->out.nal[h->out.i_nal-1].i_payload - SEI_OVERHEAD;
        overhead += h->out.nal[h->out.i_nal-1].i_payload + h->out.nal[h->out.i_nal-1].i_padding + SEI_OVERHEAD;
    }
    //写入SEI代码结束========================================================

    /* Init the rate control */
    /* FIXME: Include slice header bit cost. */
    //码率控制单元初始化
    x264_ratecontrol_start( h, h->fenc->i_qpplus1, overhead*8 );
    i_global_qp = x264_ratecontrol_qp( h );

    pic_out->i_qpplus1 =
    h->fdec->i_qpplus1 = i_global_qp + 1;

    if( h->param.rc.b_stat_read && h->sh.i_type != SLICE_TYPE_I )
    {
        x264_reference_build_list_optimal( h );
        x264_reference_check_reorder( h );
    }

    if( h->i_ref[0] )
        h->fdec->i_poc_l0ref0 = h->fref[0][0]->i_poc;

    /* ------------------------ Create slice header  ----------------------- *
    //创建Slice Header
    x264_slice_init( h, i_nal_type, i_global_qp );

    /*------------------------- Weights -------------------------------------
    //加权预测

    if( h->sh.i_type == SLICE_TYPE_B )
        x264_macroblock_bipred_init( h );

    x264_weighted_pred_init( h );

    if( i_nal_ref_idc != NAL_PRIORITY_DISPOSABLE )
        h->i_frame_num++;

    /* Write frame */
    h->i_threadslice_start = 0;
    h->i_threadslice_end = h->mb.i_mb_height;


    if( h->i_thread_frames > 1 )
    {
        x264_threadpool_run( h->threadpool, (void*)x264_slices_write, h );
        h->b_thread_active = 1;
    }
    else if( h->param.b_sliced_threads )
    {
        if( x264_threaded_slices_write( h ) )
            return -1;
    }
    else{
        //真正的编码——编码1个图像帧（注意这里“slices”后面有“s”）
        if( (intptr_t)x264_slices_write( h ) )
            return -1;
    }
    //结束的时候做一些处理，记录一些统计信息
    //输出NALU
    //输出重建帧
    return x264_encoder_frame_end( thread_oldest, thread_current, pp_nal, pi_nal, pic_out );
}
```

从源代码可以看出，x264_encoder_encode()的流程大致如下：

（1）调用x264_frame_pop_unused获取一个空的fenc（x264_frame_t类型）用于存储一帧编码像素数据。

（2）调用x264_frame_copy_picture()将外部结构体的pic_in（x264_picture_t类型）的数据拷贝给内部结构体的fenc（x264_frame_t类型）。

（3）调用x264_lookahead_put_frame()将fenc放入Lookahead模块的队列中，等待确定帧类型。

（4）调用x264_lookahead_get_frames()分析Lookahead模块中一个帧的帧类型。分析后的帧保存在frames.current[]中。

（5）调用x264_frame_shift()从frames.current[]中取出分析帧类型之后的fenc。

（6）调用x264_reference_update()更新参考帧队列frames.reference[]。

（7）如果编码帧fenc是IDR帧，调用x264_reference_reset()清空参考帧队列frames.reference[]。

（8）调用x264_reference_build_list()创建参考帧列表List0和List1。

（9）根据选项做一些配置：

a)如果b_aud不为0，输出AUD类型NALU

b)在当前帧是关键帧的情况下，如果b_repeat_headers不为0，调用x264_sps_write()和x264_pps_write()输出SPS和PPS。

c)输出一些特殊的SEI信息，用于适配各种解码器。

（10）调用x264_slice_init()初始化Slice Header信息。
（11）调用x264_slices_write()进行编码。该部分是libx264的核心，在后续文章中会详细分析。
（12）调用x264_encoder_frame_end()做一些编码后的后续处理。

下文将会按照步骤对上述函数进行简单的分析。

x264_frame_pop_unused()

x264_frame_pop_unused()用于获取1个x264_frame_t类型结构体fenc。该函数的定义位于common\frame.c，如下所示。

[cpp]

```cpp
//获取一帧的编码帧fenc或者重建帧fdec
x264_frame_t *x264_frame_pop_unused( x264_t *h, int b_fdec )
{
    x264_frame_t *frame;
    if( h->frames.unused[b_fdec][0] )//unused队列不为空
        frame = x264_frame_pop( h->frames.unused[b_fdec] );//从unused队列取
    else
        frame = x264_frame_new( h, b_fdec );//分配一帧空间
    if( !frame )
        return NULL;
    frame->b_last_minigop_bframe = 0;
    frame->i_reference_count = 1;
    frame->b_intra_calculated = 0;
    frame->b_scenecut = 1;
    frame->b_keyframe = 0;
    frame->b_corrupt = 0;
    frame->i_slice_count = h->param.b_sliced_threads ? h->param.i_threads : 1;

    memset( frame->weight, 0, sizeof(frame->weight) );
    memset( frame->f_weighted_cost_delta, 0, sizeof(frame->f_weighted_cost_delta) );

    return frame;
}
```

从源代码可以看出，如果frames.unused[]队列不为空，x264_frame_pop_unused()就调用x264_frame_pop()从unused[]队列取1个现成的；否则就调用x264_frame_new()创建一个新的。下面看一下这两个函数。

x264_frame_pop()

x264_frame_pop()用于从一个队列的尾部取出一个帧。该函数的定义位于common\frame.c，如下所示。

[cpp]

```cpp
//从队列的尾部取出一帧
x264_frame_t *x264_frame_pop( x264_frame_t **list )
{
    x264_frame_t *frame;
    int i = 0;
    assert( list[0] );
    while( list[i+1] ) i++;
    frame = list[i];
    list[i] = NULL;
    return frame;
}
```

从源代码中可以看出，x264_frame_pop()首先通过一个while()循环找到队列尾部的元素，然后将该元素作为返回值返回。

x264_frame_new()

x264_frame_new()用于新建一个x264_frame_t。该函数的定义位于common\frame.c，如下所示。

[cpp]

```cpp
//新建一个帧
//b_fdec：取1的时候为重建帧fdec，取0的时候为编码帧fenc
static x264_frame_t *x264_frame_new( x264_t *h, int b_fdec )
{
    x264_frame_t *frame;
    //注意转换后只有3种colorspace：X264_CSP_NV12(对应YUV420),X264_CSP_NV16(对应YUV422),X264_CSP_I444(对应YUV444)
    int i_csp = x264_frame_internal_csp( h->param.i_csp );
    int i_mb_count = h->mb.i_mb_count;
    int i_stride, i_width, i_lines, luma_plane_count;
    int i_padv = PADV << PARAM_INTERLACED;
    int align = 16;
#if ARCH_X86 || ARCH_X86_64
    if( h->param.cpu&X264_CPU_CACHELINE_64 )
        align = 64;
    else if( h->param.cpu&X264_CPU_CACHELINE_32 || h->param.cpu&X264_CPU_AVX2 )
```

```c
        align = 32;
#endif
#if ARCH_PPC
    int disalign = 1<<9;
#else
    int disalign = 1<<10;
#endif
    //给frame分配内存，并置零
    CHECKED_MALLOCZERO( frame, sizeof(x264_frame_t) );
    PREALLOC_INIT

    /* allocate frame data (+64 for extra data for me) */
    //以像素为单位的宽高
    i_width  = h->mb.i_mb_width*16;
    i_lines  = h->mb.i_mb_height*16;
    i_stride = align_stride( i_width + 2*PADH, align, disalign );

    if( i_csp == X264_CSP_NV12 || i_csp == X264_CSP_NV16 )
    {
        //YUV422,YUV420情况

        luma_plane_count = 1;
        frame->i_plane = 2;
        for( int i = 0; i < 2; i++ )
        {
            frame->i_width[i] = i_width >> i;
            frame->i_lines[i] = i_lines >> (i && i_csp == X264_CSP_NV12);
            frame->i_stride[i] = i_stride;
        }
    }
    else if( i_csp == X264_CSP_I444 )
    {
        //YUV444情况
        luma_plane_count = 3;
        frame->i_plane = 3;
        for( int i = 0; i < 3; i++ )
        {
            frame->i_width[i] = i_width;
            frame->i_lines[i] = i_lines;
            frame->i_stride[i] = i_stride;
        }
    }
    else
        goto fail;
    //赋值赋值赋值...
    frame->i_csp = i_csp;
    frame->i_width_lowres = frame->i_width[0]/2;
    frame->i_lines_lowres = frame->i_lines[0]/2;
    frame->i_stride_lowres = align_stride( frame->i_width_lowres + 2*PADH, align, disalign<<1 );

    for( int i = 0; i < h->param.i_bframe + 2; i++ )
        for( int j = 0; j < h->param.i_bframe + 2; j++ )
            PREALLOC( frame->i_row_satds[i][j], i_lines/16 * sizeof(int) );

    frame->i_poc = -1;
    frame->i_type = X264_TYPE_AUTO;
    frame->i_qpplus1 = X264_QP_AUTO;
    frame->i_pts = -1;
    frame->i_frame = -1;
    frame->i_frame_num = -1;
    frame->i_lines_completed = -1;
    frame->b_fdec = b_fdec;
    frame->i_pic_struct = PIC_STRUCT_AUTO;
    frame->i_field_cnt = -1;
    frame->i_duration =
    frame->i_cpb_duration =
    frame->i_dpb_output_delay =
    frame->i_cpb_delay = 0;
    frame->i_coded_fields_lookahead =
    frame->i_cpb_delay_lookahead = -1;

    frame->orig = frame;

    if( i_csp == X264_CSP_NV12 || i_csp == X264_CSP_NV16 )
    {
        int chroma_padv = i_padv >> (i_csp == X264_CSP_NV12);
        int chroma_plane_size = (frame->i_stride[1] * (frame->i_lines[1] + 2*chroma_padv));
        PREALLOC( frame->buffer[1], chroma_plane_size * sizeof(pixel) );
        if( PARAM_INTERLACED )
            PREALLOC( frame->buffer_fld[1], chroma_plane_size * sizeof(pixel) );
    }

    /* all 4 luma planes allocated together, since the cacheline split code
     * requires them to be in-phase wrt cacheline alignment. */

    for( int p = 0; p < luma_plane_count; p++ )
    {
        int luma_plane_size = align_plane_size( frame->i_stride[p] * (frame->i_lines[p] + 2*i_padv), disalign );
        if( h->param.analyse.i_subpel_refine && b_fdec )
        {
            /* FIXME: Don't allocate both buffers in non-adaptive MBAFF. */
```

```
            PREALLOC( frame->buffer[p], 4*luma_plane_size * sizeof(pixel) );
            if( PARAM_INTERLACED )
                PREALLOC( frame->buffer_fld[p], 4*luma_plane_size * sizeof(pixel) );
        }
        else
        {
            PREALLOC( frame->buffer[p], luma_plane_size * sizeof(pixel) );
            if( PARAM_INTERLACED )
                PREALLOC( frame->buffer_fld[p], luma_plane_size * sizeof(pixel) );
        }
    }

    frame->b_duplicate = 0;

    if( b_fdec ) /* fdec frame */
    {
        //重建帧fdec
        PREALLOC( frame->mb_type, i_mb_count * sizeof(int8_t) );
        PREALLOC( frame->mb_partition, i_mb_count * sizeof(uint8_t) );
        PREALLOC( frame->mv[0], 2*16 * i_mb_count * sizeof(int16_t) );
        PREALLOC( frame->mv16x16, 2*(i_mb_count+1) * sizeof(int16_t) );
        PREALLOC( frame->ref[0], 4 * i_mb_count * sizeof(int8_t) );
        if( h->param.i_bframe )
        {
            PREALLOC( frame->mv[1], 2*16 * i_mb_count * sizeof(int16_t) );
            PREALLOC( frame->ref[1], 4 * i_mb_count * sizeof(int8_t) );
        }
        else
        {
            frame->mv[1]  = NULL;
            frame->ref[1] = NULL;
        }
        PREALLOC( frame->i_row_bits, i_lines/16 * sizeof(int) );
        PREALLOC( frame->f_row_qp, i_lines/16 * sizeof(float) );
        PREALLOC( frame->f_row_qscale, i_lines/16 * sizeof(float) );
        if( h->param.analyse.i_me_method >= X264_ME_ESA )
            PREALLOC( frame->buffer[3], frame->i_stride[0] * (frame->i_lines[0] + 2*i_padv) * sizeof(uint16_t) << h->frames.b_have_sub8x8_esa );
        if( PARAM_INTERLACED )
            PREALLOC( frame->field, i_mb_count * sizeof(uint8_t) );
        if( h->param.analyse.b_mb_info )
            PREALLOC( frame->effective_qp, i_mb_count * sizeof(uint8_t) );
    }
    else /* fenc frame */
    {
        //编码帧fenc
        if( h->frames.b_have_lowres )
        {
            int luma_plane_size = align_plane_size( frame->i_stride_lowres * (frame->i_lines[0]/2 + 2*PADV), disalign );

            PREALLOC( frame->buffer_lowres[0], 4 * luma_plane_size * sizeof(pixel) );

            for( int j = 0; j <= !!h->param.i_bframe; j++ )
                for( int i = 0; i <= h->param.i_bframe; i++ )
                {
                    PREALLOC( frame->lowres_mvs[j][i], 2*h->mb.i_mb_count*sizeof(int16_t) );
                    PREALLOC( frame->lowres_mv_costs[j][i], h->mb.i_mb_count*sizeof(int) );
                }
            PREALLOC( frame->i_propagate_cost, (i_mb_count+7) * sizeof(uint16_t) );
            for( int j = 0; j <= h->param.i_bframe+1; j++ )
                for( int i = 0; i <= h->param.i_bframe+1; i++ )
                    PREALLOC( frame->lowres_costs[j][i], (i_mb_count+3) * sizeof(uint16_t) );

        }
        if( h->param.rc.i_aq_mode )
        {
            PREALLOC( frame->f_qp_offset, h->mb.i_mb_count * sizeof(float) );
            PREALLOC( frame->f_qp_offset_aq, h->mb.i_mb_count * sizeof(float) );
            if( h->frames.b_have_lowres )
                PREALLOC( frame->i_inv_qscale_factor, (h->mb.i_mb_count+3) * sizeof(uint16_t) );
        }
    }

    PREALLOC_END( frame->base );

    if( i_csp == X264_CSP_NV12 || i_csp == X264_CSP_NV16 )
    {
        int chroma_padv = i_padv >> (i_csp == X264_CSP_NV12);
        frame->plane[1] = frame->buffer[1] + frame->i_stride[1] * chroma_padv + PADH;
        if( PARAM_INTERLACED )
            frame->plane_fld[1] = frame->buffer_fld[1] + frame->i_stride[1] * chroma_padv + PADH;
    }

    for( int p = 0; p < luma_plane_count; p++ )
    {
        int luma_plane_size = align_plane_size( frame->i_stride[p] * (frame->i_lines[p] + 2*i_padv), disalign );
        if( h->param.analyse.i_subpel_refine && b_fdec )
        {
            for( int i = 0; i < 4; i++ )
            {
                frame->filtered[p][i] = frame->buffer[p] + i*luma_plane_size + frame->i_stride[p] * i_padv + PADH;
                frame->filtered_fld[p][i] = frame->buffer_fld[p] + i*luma_plane_size + frame->i_stride[p] * i_padv + PADH;
```

```
                frame->filtered_fld[p][i] = frame->buffer_fld[p] + i*luma_plane_size + frame->i_stride[p] * i_padv + PADH;
            }
            frame->plane[p] = frame->filtered[p][0];
            frame->plane_fld[p] = frame->filtered_fld[p][0];
        }
        else
        {
            frame->filtered[p][0] = frame->plane[p] = frame->buffer[p] + frame->i_stride[p] * i_padv + PADH;
            frame->filtered_fld[p][0] = frame->plane_fld[p] = frame->buffer_fld[p] + frame->i_stride[p] * i_padv + PADH;
        }
    }

    if( b_fdec )
    {
        M32( frame->mv16x16[0] ) = 0;
        frame->mv16x16++;

        if( h->param.analyse.i_me_method >= X264_ME_ESA )
            frame->integral = (uint16_t*)frame->buffer[3] + frame->i_stride[0] * i_padv + PADH;
    }
    else
    {
        if( h->frames.b_have_lowres )
        {
            int luma_plane_size = align_plane_size( frame->i_stride_lowres * (frame->i_lines[0]/2 + 2*PADV), disalign );
            for( int i = 0; i < 4; i++ )
                frame->lowres[i] = frame->buffer_lowres[0] + (frame->i_stride_lowres * PADV + PADH) + i * luma_plane_size;

            for( int j = 0; j <= !!h->param.i_bframe; j++ )
                for( int i = 0; i <= h->param.i_bframe; i++ )
                    memset( frame->lowres_mvs[j][i], 0, 2*h->mb.i_mb_count*sizeof(int16_t) );

            frame->i_intra_cost = frame->lowres_costs[0][0];
            memset( frame->i_intra_cost, -1, (i_mb_count+3) * sizeof(uint16_t) );

            if( h->param.rc.i_aq_mode )
                /* shouldn't really be initialized, just silences a valgrind false-positive in x264_mbtree_propagate_cost_sse2 */
                memset( frame->i_inv_qscale_factor, 0, (h->mb.i_mb_count+3) * sizeof(uint16_t) );
        }
    }

    if( x264_pthread_mutex_init( &frame->mutex, NULL ) )
        goto fail;
    if( x264_pthread_cond_init( &frame->cv, NULL ) )
        goto fail;

#if HAVE_OPENCL
    frame->opencl.ocl = h->opencl.ocl;
#endif

    return frame;

fail:
    x264_free( frame );
    return NULL;
}
```

从源代码中可以看出，x264_frame_new()声明了一个frame指针，并在后续过程中对该frame的成员变量进行内存分配和注释。需要注意的是编码帧fenc和重建帧fdec初始化的变量是不一样的——函数的输入参数b_fdec不为0的时候初始化重建帧，否则初始化编码帧。在这个函数中涉及到一个简单的函数x264_frame_internal_csp()，用于把种类繁多的外部Colorspace转换为简单的内部Colorspace。

x264_frame_internal_csp()

x264_frame_internal_csp()用于把外部Colorspace转换为内部Colorspace。该函数的定义如下所示。

```cpp
//注意转换后只有3种内部colorspace：X264_CSP_NV12(对应YUV420),X264_CSP_NV16(对应YUV422),X264_CSP_I444(对应YUV444)
static int x264_frame_internal_csp( int external_csp )
{
    switch( external_csp & X264_CSP_MASK )
    {
        case X264_CSP_NV12:
        case X264_CSP_I420:
        case X264_CSP_YV12:
            return X264_CSP_NV12;
        case X264_CSP_NV16:
        case X264_CSP_I422:
        case X264_CSP_YV16:
        case X264_CSP_V210:
            return X264_CSP_NV16;
        case X264_CSP_I444:
        case X264_CSP_YV24:
        case X264_CSP_BGR:
        case X264_CSP_BGRA:
        case X264_CSP_RGB:
            return X264_CSP_I444;
        default:
            return X264_CSP_NONE;
    }
}
```

x264_frame_copy_picture()

x264_frame_copy_picture()用于将外部结构体x264_picture_t的数据拷贝给内部结构体x264_frame_t。该函数的定义位于common\frame.c，如下所示。

```cpp
//拷贝帧数据
//src（外部结构体x264_picture_t）到dst（内部结构体x264_frame_t）
int x264_frame_copy_picture( x264_t *h, x264_frame_t *dst, x264_picture_t *src )
{
    int i_csp = src->img.i_csp & X264_CSP_MASK;
    //注意转换后只有3种内部colorspace：X264_CSP_NV12(对应YUV420),X264_CSP_NV16(对应YUV422),X264_CSP_I444(对应YUV444)
    if( dst->i_csp != x264_frame_internal_csp( i_csp ) )
    {
        x264_log( h, X264_LOG_ERROR, "Invalid input colorspace\n" );
        return -1;
    }

#if HIGH_BIT_DEPTH
    if( !(src->img.i_csp & X264_CSP_HIGH_DEPTH) )
    {
        x264_log( h, X264_LOG_ERROR, "This build of x264 requires high depth input. Rebuild to support 8-bit input.\n" );
        return -1;
    }
#else
    if( src->img.i_csp & X264_CSP_HIGH_DEPTH )
    {
        x264_log( h, X264_LOG_ERROR, "This build of x264 requires 8-bit input. Rebuild to support high depth input.\n" );
        return -1;
    }
#endif

    if( BIT_DEPTH != 10 && i_csp == X264_CSP_V210 )
    {
        x264_log( h, X264_LOG_ERROR, "v210 input is only compatible with bit-depth of 10 bits\n" );
        return -1;
    }
    //赋值赋值赋值
    dst->i_type     = src->i_type;
    dst->i_qpplus1  = src->i_qpplus1;
    dst->i_pts      = dst->i_reordered_pts = src->i_pts;
    dst->param      = src->param;
    dst->i_pic_struct = src->i_pic_struct;
    dst->extra_sei  = src->extra_sei;
    dst->opaque     = src->opaque;
    dst->mb_info    = h->param.analyse.b_mb_info ? src->prop.mb_info : NULL;
    dst->mb_info_free = h->param.analyse.b_mb_info ? src->prop.mb_info_free : NULL;

    uint8_t *pix[3];
    int stride[3];
    if( i_csp == X264_CSP_V210 )
    {
         stride[0] = src->img.i_stride[0];
         pix[0] = src->img.plane[0];

         h->mc.plane_copy_deinterleave_v210( dst->plane[0], dst->i_stride[0],
                                             dst->plane[1], dst->i_stride[1],
                                             (uint32_t *)pix[0], stride[0]/sizeof(uint32_t), h->param.i_width, h-
>param.i_height );
```

```cpp
    }
    else if( i_csp >= X264_CSP_BGR )
    {
         stride[0] = src->img.i_stride[0];
         pix[0] = src->img.plane[0];
         if( src->img.i_csp & X264_CSP_VFLIP )
         {
             pix[0] += (h->param.i_height-1) * stride[0];
             stride[0] = -stride[0];
         }
         int b = i_csp==X264_CSP_RGB;
         h->mc.plane_copy_deinterleave_rgb( dst->plane[1+b], dst->i_stride[1+b],
                                            dst->plane[0], dst->i_stride[0],
                                            dst->plane[2-b], dst->i_stride[2-b],
                                            (pixel*)pix[0], stride[0]/sizeof(pixel), i_csp==X264_CSP_BGRA ? 4 : 3, h->param.i_width, h->param.i_height );
    }
    else
    {
        int v_shift = CHROMA_V_SHIFT;
        get_plane_ptr( h, src, &pix[0], &stride[0], 0, 0, 0 );
        //拷贝像素
        h->mc.plane_copy( dst->plane[0], dst->i_stride[0], (pixel*)pix[0],
                          stride[0]/sizeof(pixel), h->param.i_width, h->param.i_height );
        if( i_csp == X264_CSP_NV12 || i_csp == X264_CSP_NV16 )
        {
            get_plane_ptr( h, src, &pix[1], &stride[1], 1, 0, v_shift );
            h->mc.plane_copy( dst->plane[1], dst->i_stride[1], (pixel*)pix[1],
                              stride[1]/sizeof(pixel), h->param.i_width, h->param.i_height>>v_shift );
        }
        else if( i_csp == X264_CSP_I420 || i_csp == X264_CSP_I422 || i_csp == X264_CSP_YV12 || i_csp == X264_CSP_YV16 )
        {
            int uv_swap = i_csp == X264_CSP_YV12 || i_csp == X264_CSP_YV16;
            get_plane_ptr( h, src, &pix[1], &stride[1], uv_swap ? 2 : 1, 1, v_shift );
            get_plane_ptr( h, src, &pix[2], &stride[2], uv_swap ? 1 : 2, 1, v_shift );
            h->mc.plane_copy_interleave( dst->plane[1], dst->i_stride[1],
                                         (pixel*)pix[1], stride[1]/sizeof(pixel),
                                         (pixel*)pix[2], stride[2]/sizeof(pixel),
                                         h->param.i_width>>1, h->param.i_height>>v_shift );
        }
        else //if( i_csp == X264_CSP_I444 || i_csp == X264_CSP_YV24 )
        {
            get_plane_ptr( h, src, &pix[1], &stride[1], i_csp==X264_CSP_I444 ? 1 : 2, 0, 0 );
            get_plane_ptr( h, src, &pix[2], &stride[2], i_csp==X264_CSP_I444 ? 2 : 1, 0, 0 );
            h->mc.plane_copy( dst->plane[1], dst->i_stride[1], (pixel*)pix[1],
                              stride[1]/sizeof(pixel), h->param.i_width, h->param.i_height );
            h->mc.plane_copy( dst->plane[2], dst->i_stride[2], (pixel*)pix[2],
                              stride[2]/sizeof(pixel), h->param.i_width, h->param.i_height );
        }
    }
    return 0;
}
```

从源代码可以看出，x264_frame_t和x264_picture_t结构体中很多字段是一模一样的，x264_frame_copy_picture()只是简单地将x264_picture_t中字段的值赋值给了x264_frame_t。

x264_lookahead_put_frame()

x264_lookahead_put_frame()将编码帧放入Lookahead模块的队列中，等待确定帧类型。该函数的定义位于encoder\lookahead.c，如下所示。

[cpp]

```cpp
//x264_frame_t放入x264_sync_frame_list_t队列
void x264_lookahead_put_frame( x264_t *h, x264_frame_t *frame )
{
    if( h->param.i_sync_lookahead )
        x264_sync_frame_list_push( &h->lookahead->ifbuf, frame );
    else
        x264_sync_frame_list_push( &h->lookahead->next, frame );//放入next队列
}
```

从源代码可以看出，i_sync_lookahead不为0的时候，会将编码帧放入lookahead.ifbuf[]中，否则会将编码帧放入lookahead.next[]中。放入帧的时候会调用x264_sync_frame_list_push()。

x264_sync_frame_list_push()

x264_sync_frame_list_push()用于向x264_sync_frame_list_t类型的队列中放入一个帧。该函数的定义位于common\frame.c，如下所示。

```cpp
void x264_sync_frame_list_push( x264_sync_frame_list_t *slist, x264_frame_t *frame )
{
    x264_pthread_mutex_lock( &slist->mutex );
    while( slist->i_size == slist->i_max_size )
        x264_pthread_cond_wait( &slist->cv_empty, &slist->mutex );
    //放入
    slist->list[ slist->i_size++ ] = frame;
    x264_pthread_mutex_unlock( &slist->mutex );
    x264_pthread_cond_broadcast( &slist->cv_fill );
}
```

从源代码中可以看出，x264_sync_frame_list_push()将frame放在了x264_sync_frame_list_t.list的尾部。

x264_lookahead_get_frames()

x264_lookahead_get_frames()通过lookahead模块分析帧类型。该函数的定义位于encoder\lookahead.c，如下所示。

```cpp
//通过lookahead分析帧类型
void x264_lookahead_get_frames( x264_t *h )
{
    if( h->param.i_sync_lookahead )
    {   /* We have a lookahead thread, so get frames from there */
        x264_pthread_mutex_lock( &h->lookahead->ofbuf.mutex );
        while( !h->lookahead->ofbuf.i_size && h->lookahead->b_thread_active )
            x264_pthread_cond_wait( &h->lookahead->ofbuf.cv_fill, &h->lookahead->ofbuf.mutex );
        x264_lookahead_encoder_shift( h );
        x264_pthread_mutex_unlock( &h->lookahead->ofbuf.mutex );
    }
    else
    {   /* We are not running a lookahead thread, so perform all the slicetype decide on the fly */
        //currect[]必须为空，next不能为空？
        if( h->frames.current[0] || !h->lookahead->next.i_size )
            return;
        //分析lookahead->next->list帧的类型
        x264_stack_align( x264_slicetype_decide, h );
        //更新lookahead->last_nonb
        x264_lookahead_update_last_nonb( h, h->lookahead->next.list[0] );
        int shift_frames = h->lookahead->next.list[0]->i_bframes + 1;
        //lookahead->next.list移动到lookahead->ofbuf.list
        x264_lookahead_shift( &h->lookahead->ofbuf, &h->lookahead->next, shift_frames );

        /* For MB-tree and VBV lookahead, we have to perform propagation analysis on I-frames too. */
        if( h->lookahead->b_analyse_keyframe && IS_X264_TYPE_I( h->lookahead->last_nonb->i_type ) )
            x264_stack_align( x264_slicetype_analyse, h, shift_frames );

        //lookahead->ofbuf.list帧移动到frames->current
        x264_lookahead_encoder_shift( h );
    }
}
```

从源代码中可以看出，x264_lookahead_get_frames()调用了x264_slicetype_decide()用于确定帧类型。在这里需要注意，Lookahead模块的代码量比较大，暂时不做详细的分析，仅简单理一下脉络。

x264_slicetype_decide()

x264_slicetype_decide()用于确定帧类型，该函数的定义位于encoder\slicetype.c，如下所示。

```cpp
//确定帧的类型（I、B、P）
void x264_slicetype_decide( x264_t *h )
{
    x264_frame_t *frames[X264_BFRAME_MAX+2];
    x264_frame_t *frm;
    int bframes;
    int brefs;

    if( !h->lookahead->next.i_size )
        return;

    int lookahead_size = h->lookahead->next.i_size;

    //遍历next队列
    for( int i = 0; i < h->lookahead->next.i_size; i++ )
    {
        if( h->param.b_vfr_input )
        {
            if( lookahead_size-- > 1 )
                h->lookahead->next.list[i]->i_duration = 2 * (h->lookahead->next.list[i+1]->i_pts - h->lookahead->next.list[i]->i_pt
s);
            else
```

```
                h->lookahead->next.list[i]->i_duration = h->i_prev_duration;
        }
        else
            h->lookahead->next.list[i]->i_duration = delta_tfi_divisor[h->lookahead->next.list[i]->i_pic_struct];
        h->i_prev_duration = h->lookahead->next.list[i]->i_duration;
        h->lookahead->next.list[i]->f_duration = (double)h->lookahead->next.list[i]->i_duration
                                               * h->sps->vui.i_num_units_in_tick
                                               / h->sps->vui.i_time_scale;

        if( h->lookahead->next.list[i]->i_frame > h->i_disp_fields_last_frame && lookahead_size > 0 )
        {
            h->lookahead->next.list[i]->i_field_cnt = h->i_disp_fields;
            h->i_disp_fields += h->lookahead->next.list[i]->i_duration;
            h->i_disp_fields_last_frame = h->lookahead->next.list[i]->i_frame;
        }
        else if( lookahead_size == 0 )
        {
            h->lookahead->next.list[i]->i_field_cnt = h->i_disp_fields;
            h->lookahead->next.list[i]->i_duration = h->i_prev_duration;
        }
    }

    if( h->param.rc.b_stat_read )
    {
        //b_stat_read在2pass模式的第2遍才不为0

        /* Use the frame types from the first pass */
        for( int i = 0; i < h->lookahead->next.i_size; i++ )
            h->lookahead->next.list[i]->i_type =
                x264_ratecontrol_slice_type( h, h->lookahead->next.list[i]->i_frame );
    }
    else if( (h->param.i_bframe && h->param.i_bframe_adaptive)
             || h->param.i_scenecut_threshold
             || h->param.rc.b_mb_tree
             || (h->param.rc.i_vbv_buffer_size && h->param.rc.i_lookahead) )
        x264_slicetype_analyse( h, 0 );//分析帧的类型（I、B、P）
    //======================================================================

    for( bframes = 0, brefs = 0;; bframes++ )
    {
        //从next队列取出1个
        frm = h->lookahead->next.list[bframes];
        //BREF的处理
        if( frm->i_type == X264_TYPE_BREF && h->param.i_bframe_pyramid < X264_B_PYRAMID_NORMAL &&
            brefs == h->param.i_bframe_pyramid )
        {
            //BREF改成B
            frm->i_type = X264_TYPE_B;
            x264_log( h, X264_LOG_WARNING, "B-ref at frame %d incompatible with B-pyramid %s \n",
                      frm->i_frame, x264_b_pyramid_names[h->param.i_bframe_pyramid] );
        }
        /* pyramid with multiple B-refs needs a big enough dpb that the preceding P-frame stays available.
           smaller dpb could be supported by smart enough use of mmco, but it's easier just to forbid it. */
        else if( frm->i_type == X264_TYPE_BREF && h->param.i_bframe_pyramid == X264_B_PYRAMID_NORMAL &&
            brefs && h->param.i_frame_reference <= (brefs+3) )
        {
            frm->i_type = X264_TYPE_B;
            x264_log( h, X264_LOG_WARNING, "B-ref at frame %d incompatible with B-pyramid %s and %d reference frames\n",
                      frm->i_frame, x264_b_pyramid_names[h->param.i_bframe_pyramid], h->param.i_frame_reference );
        }
        //Keyframe处理
        if( frm->i_type == X264_TYPE_KEYFRAME )
            frm->i_type = h->param.b_open_gop ? X264_TYPE_I : X264_TYPE_IDR;

        /* Limit GOP size */
        if( (!h->param.b_intra_refresh || frm->i_frame == 0) && frm->i_frame - h->lookahead->i_last_keyframe >= h->param.i_keyint_max )
        {
            if( frm->i_type == X264_TYPE_AUTO || frm->i_type == X264_TYPE_I )
                frm->i_type = h->param.b_open_gop && h->lookahead->i_last_keyframe >= 0 ? X264_TYPE_I : X264_TYPE_IDR;
            int warn = frm->i_type != X264_TYPE_IDR;
            if( warn && h->param.b_open_gop )
                warn &= frm->i_type != X264_TYPE_I;
            if( warn )
            {
                x264_log( h, X264_LOG_WARNING, "specified frame type (%d) at %d is not compatible with keyframe interval\n", frm->i_type, frm->i_frame );
                frm->i_type = h->param.b_open_gop && h->lookahead->i_last_keyframe >= 0 ? X264_TYPE_I : X264_TYPE_IDR;
            }
        }
        if( frm->i_type == X264_TYPE_I && frm->i_frame - h->lookahead->i_last_keyframe >= h->param.i_keyint_min )
        {
            if( h->param.b_open_gop )
            {
                h->lookahead->i_last_keyframe = frm->i_frame; // Use display order
                if( h->param.b_bluray_compat )
                    h->lookahead->i_last_keyframe -= bframes; // Use bluray order
                frm->b_keyframe = 1;
            }
            else
                frm->i_type = X264_TYPE_IDR;
```

```
        }
        if( frm->i_type == X264_TYPE_IDR )
        {
            /* Close GOP */
            //设置当前帧为“上一个关键帧”
            h->lookahead->i_last_keyframe = frm->i_frame;
            frm->b_keyframe = 1;
            if( bframes > 0 )
            {
                bframes--;
                h->lookahead->next.list[bframes]->i_type = X264_TYPE_P;
            }
        }

        if( bframes == h->param.i_bframe ||
            !h->lookahead->next.list[bframes+1] )
        {
            if( IS_X264_TYPE_B( frm->i_type ) )
                x264_log( h, X264_LOG_WARNING, "specified frame type is not compatible with max B-frames\n" );
            if( frm->i_type == X264_TYPE_AUTO
                || IS_X264_TYPE_B( frm->i_type ) )
                frm->i_type = X264_TYPE_P;
        }

        if( frm->i_type == X264_TYPE_BREF )
            brefs++;

        if( frm->i_type == X264_TYPE_AUTO )
            frm->i_type = X264_TYPE_B;

        else if( !IS_X264_TYPE_B( frm->i_type ) ) break;
    }

    if( bframes )
        h->lookahead->next.list[bframes-1]->b_last_minigop_bframe = 1;
    h->lookahead->next.list[bframes]->i_bframes = bframes;

    /* insert a bref into the sequence */
    if( h->param.i_bframe_pyramid && bframes > 1 && !brefs )
    {
        h->lookahead->next.list[bframes/2]->i_type = X264_TYPE_BREF;
        brefs++;
    }

    /* calculate the frame costs ahead of time for x264_rc_analyse_slice while we still have lowres */
    if( h->param.rc.i_rc_method != X264_RC_CQP )
    {
        x264_mb_analysis_t a;
        int p0, p1, b;
        p1 = b = bframes + 1;

        x264_lowres_context_init( h, &a );

        frames[0] = h->lookahead->last_nonb;
        memcpy( &frames[1], h->lookahead->next.list, (bframes+1) * sizeof(x264_frame_t*) );
        if( IS_X264_TYPE_I( h->lookahead->next.list[bframes]->i_type ) )
            p0 = bframes + 1;
        else // P
            p0 = 0;

        x264_slicetype_frame_cost( h, &a, frames, p0, p1, b, 0 );

        if( (p0 != p1 || bframes) && h->param.rc.i_vbv_buffer_size )
        {
            /* We need the intra costs for row SATDs. */
            x264_slicetype_frame_cost( h, &a, frames, b, b, b, 0 );

            /* We need B-frame costs for row SATDs. */
            p0 = 0;
            for( b = 1; b <= bframes; b++ )
            {
                if( frames[b]->i_type == X264_TYPE_B )
                    for( p1 = b; frames[p1]->i_type == X264_TYPE_B; )
                        p1++;
                else
                    p1 = bframes + 1;
                x264_slicetype_frame_cost( h, &a, frames, p0, p1, b, 0 );
                if( frames[b]->i_type == X264_TYPE_BREF )
                    p0 = b;
            }
        }
    }

    /* Analyse for weighted P frames */
    if( !h->param.rc.b_stat_read && h->lookahead->next.list[bframes]->i_type == X264_TYPE_P
        && h->param.analyse.i_weighted_pred >= X264_WEIGHTP_SIMPLE )
    {
        x264_emms();
        x264_weights_analyse( h, h->lookahead->next.list[bframes], h->lookahead->last_nonb, 0 );
    }

```

```cpp
    /* shift sequence to coded order.
       use a small temporary list to avoid shifting the entire next buffer around */
    int i_coded = h->lookahead->next.list[0]->i_frame;
    if( bframes )
    {
        int idx_list[] = { brefs+1, 1 };
        for( int i = 0; i < bframes; i++ )
        {
            int idx = idx_list[h->lookahead->next.list[i]->i_type == X264_TYPE_BREF]++;
            frames[idx] = h->lookahead->next.list[i];
            frames[idx]->i_reordered_pts = h->lookahead->next.list[idx]->i_pts;
        }
        frames[0] = h->lookahead->next.list[bframes];
        frames[0]->i_reordered_pts = h->lookahead->next.list[0]->i_pts;
        memcpy( h->lookahead->next.list, frames, (bframes+1) * sizeof(x264_frame_t*) );
    }

    for( int i = 0; i <= bframes; i++ )
    {
        h->lookahead->next.list[i]->i_coded = i_coded++;
        if( i )
        {
            x264_calculate_durations( h, h->lookahead->next.list[i], h->lookahead->next.list[i-1], &h->i_cpb_delay, &h->i_coded_fields );
            h->lookahead->next.list[0]->f_planned_cpb_duration[i-1] = (double)h->lookahead->next.list[i]->i_cpb_duration *
                                                                      h->sps->vui.i_num_units_in_tick / h->sps->vui.i_time_scale;
        }
        else
            x264_calculate_durations( h, h->lookahead->next.list[i], NULL, &h->i_cpb_delay, &h->i_coded_fields );
    }
}
```

x264_slicetype_decide()源代码比较长，还没有细看。该函数中调用了一个比较重要的函数x264_slicetype_analyse()。

x264_slicetype_analyse()

x264_slicetype_analyse()用于分析帧类型。该函数的定义位于encoder\slicetype.c，如下所示。

[cpp]

```cpp
//分析帧的类型（I、B、P）
void x264_slicetype_analyse( x264_t *h, int intra_minigop )
{
    x264_mb_analysis_t a;
    x264_frame_t *frames[X264_LOOKAHEAD_MAX+3] = { NULL, };
    int num_frames, orig_num_frames, keyint_limit, framecnt;
    int i_mb_count = NUM_MBS;
    int cost1p0, cost2p0, cost1b1, cost2p1;
    // 确定最大的搜索长度
    // 在我的调试当中， h->lookahead->next.i_size = 4
    int i_max_search = X264_MIN( h->lookahead->next.i_size, X264_LOOKAHEAD_MAX );
    int vbv_lookahead = h->param.rc.i_vbv_buffer_size && h->param.rc.i_lookahead;
    /* For determinism we should limit the search to the number of frames lookahead has for sure
     * in h->lookahead->next.list buffer, except at the end of stream.
     * For normal calls with (intra_minigop == 0) that is h->lookahead->i_slicetype_length + 1 frames.
     * And for I-frame calls (intra_minigop != 0) we already removed intra_minigop frames from there. */
    if( h->param.b_deterministic )
        i_max_search = X264_MIN( i_max_search, h->lookahead->i_slicetype_length + 1 - intra_minigop );
    int keyframe = !!intra_minigop;

    assert( h->frames.b_have_lowres );

    if( !h->lookahead->last_nonb )
        return;
    //frames[0]指向上一次的非B帧
    frames[0] = h->lookahead->last_nonb;
    //frames[] 依次指向 lookahead->next链表中的帧
    for( framecnt = 0; framecnt < i_max_search && h->lookahead->next.list[framecnt]->i_type == X264_TYPE_AUTO; framecnt++ )
        frames[framecnt+1] = h->lookahead->next.list[framecnt];

    x264_lowres_context_init( h, &a );

    if( !framecnt )
    {
        if( h->param.rc.b_mb_tree )
            x264_macroblock_tree( h, &a, frames, 0, keyframe );
        return;
    }

    keyint_limit = h->param.i_keyint_max - frames[0]->i_frame + h->lookahead->i_last_keyframe - 1;
    orig_num_frames = num_frames = h->param.b_intra_refresh ? framecnt : X264_MIN( framecnt, keyint_limit );

    /* This is important psy-wise: if we have a non-scenecut keyframe,
     * there will be significant visual artifacts if the frames just before
     * go down in quality due to being referenced less, despite it being
     * more RD-optimal. */
    if( (h->param.analyse.b_psy && h->param.rc.b_mb_tree) || vbv_lookahead )
        num_frames = framecnt;
    else if( h->param.b_open_gop && num_frames < framecnt )
```

```
    else if( h->param.b_open_gop && num_frames < framecnt )
        num_frames++;
    else if( num_frames == 0 )
    {
        frames[1]->i_type = X264_TYPE_I;
        return;
    }

    int num_bframes = 0;
    int num_analysed_frames = num_frames;
    int reset_start;
    //通过scenecut()函数判断是否有场景切换，从而确定I帧
    if( h->param.i_scenecut_threshold && scenecut( h, &a, frames, 0, 1, 1, orig_num_frames, i_max_search ) )
    {
        frames[1]->i_type = X264_TYPE_I;
        return;
    }

#if HAVE_OPENCL
    x264_opencl_slicetype_prep( h, frames, num_frames, a.i_lambda );
#endif
    //允许有B帧的时候
    if( h->param.i_bframe )
    {
        if( h->param.i_bframe_adaptive == X264_B_ADAPT_TRELLIS )
        {
            if( num_frames > 1 )
            {
                char best_paths[X264_BFRAME_MAX+1][X264_LOOKAHEAD_MAX+1] = {"","P"};
                int best_path_index = num_frames % (X264_BFRAME_MAX+1);

                /* Perform the frametype analysis. */
                for( int j = 2; j <= num_frames; j++ )
                    x264_slicetype_path( h, &a, frames, j, best_paths );

                num_bframes = strspn( best_paths[best_path_index], "B" );
                /* Load the results of the analysis into the frame types. */
                for( int j = 1; j < num_frames; j++ )
                    frames[j]->i_type = best_paths[best_path_index][j-1] == 'B' ? X264_TYPE_B : X264_TYPE_P;
            }
            frames[num_frames]->i_type = X264_TYPE_P;
        }
        else if( h->param.i_bframe_adaptive == X264_B_ADAPT_FAST )
        {
            for( int i = 0; i <= num_frames-2; )
            {
                //i+2作为P帧编码的代价
                //注：i+2始终为P帧
                cost2p1 = x264_slicetype_frame_cost( h, &a, frames, i+0, i+2, i+2, 1 );
                if( frames[i+2]->i_intra_mbs[2] > i_mb_count / 2 )
                {
                    frames[i+1]->i_type = X264_TYPE_P;
                    frames[i+2]->i_type = X264_TYPE_P;
                    i += 2;
                    continue;
                }

#if HAVE_OPENCL
                if( h->param.b_opencl )
                {
                    int b_work_done = 0;
                    b_work_done |= x264_opencl_precalculate_frame_cost(h, frames, a.i_lambda, i+0, i+2, i+1 );
                    b_work_done |= x264_opencl_precalculate_frame_cost(h, frames, a.i_lambda, i+0, i+1, i+1 );
                    b_work_done |= x264_opencl_precalculate_frame_cost(h, frames, a.i_lambda, i+1, i+2, i+2 );
                    if( b_work_done )
                        x264_opencl_flush( h );
                }
#endif
                //计算代价
                //x264_slicetype_frame_cost(,,,p0,p1,b,)
                //p0 b p1
                //p1!=b为B帧，否则为P帧

                // i + 1 作为B帧编码的代价
                cost1b1 = x264_slicetype_frame_cost( h, &a, frames, i+0, i+2, i+1, 0 );
                // i + 1 作为P帧编码的代价
                cost1p0 = x264_slicetype_frame_cost( h, &a, frames, i+0, i+1, i+1, 0 );
                // i + 2 作为P帧编码的代价
                cost2p0 = x264_slicetype_frame_cost( h, &a, frames, i+1, i+2, i+2, 0 );
                //如果i+1作为P帧编码的代价  + i+2作为P帧编码的代价
                //小于 i+1作为B帧编码的代价   + i+2作为P帧编码的代价
                if( cost1p0 + cost2p0 < cost1b1 + cost2p1 )
                {
                    //那么i+1将作为P帧编码
                    //然后直接continue
                    frames[i+1]->i_type = X264_TYPE_P;
                    i += 1;
                    continue;
                }

                // arbitrary and untuned
                #define INTER_THRESH 300
```

```
                #define P_SENS_BIAS (50 - h->param.i_bframe_bias)

                // i+1 将作为B帧编码
                frames[i+1]->i_type = X264_TYPE_B;

                int j;
                for( j = i+2; j <= X264_MIN( i+h->param.i_bframe, num_frames-1 ); j++ )
                {
                    int pthresh = X264_MAX(INTER_THRESH - P_SENS_BIAS * (j-i-1), INTER_THRESH/10);
                    // 预测j+1作为P帧编码代价
                    int pcost = x264_slicetype_frame_cost( h, &a, frames, i+0, j+1, j+1, 1 );
                    // 如果pcost 满足下述条件， 则确定了一个P帧，跳出循环
                    if( pcost > pthresh*i_mb_count || frames[j+1]->i_intra_mbs[j-i+1] > i_mb_count/3 )
                        break;
                    // 否则就是B帧
                    frames[j]->i_type = X264_TYPE_B;
                }
                // 将j帧确定为P帧
                frames[j]->i_type = X264_TYPE_P;
                i = j;
            }
            // 最后一帧确定为P帧
            frames[num_frames]->i_type = X264_TYPE_P;
            num_bframes = 0;
            // 确定有多少个B帧
            while( num_bframes < num_frames && frames[num_bframes+1]->i_type == X264_TYPE_B )
                num_bframes++;
        }
        else
        {
            // 确定多少B帧
            num_bframes = X264_MIN(num_frames-1, h->param.i_bframe);
            // 每num_bframes + 1一个P帧， 其余皆为B帧
            for( int j = 1; j < num_frames; j++ )
                frames[j]->i_type = (j%(num_bframes+1)) ? X264_TYPE_B : X264_TYPE_P;
            // 最后一帧为P帧
            frames[num_frames]->i_type = X264_TYPE_P;
        }

        /* Check scenecut on the first minigop. */
        // 如果B帧中， 有帧有场景切换， 则改变其为P帧
        for( int j = 1; j < num_bframes+1; j++ )
            if( h->param.i_scenecut_threshold && scenecut( h, &a, frames, j, j+1, 0, orig_num_frames, i_max_search ) )
            {
                frames[j]->i_type = X264_TYPE_P;
                num_analysed_frames = j;
                break;
            }

        reset_start = keyframe ? 1 : X264_MIN( num_bframes+2, num_analysed_frames+1 );
    }
    else
    {
        //h->param.i_bframe为 0
        //则所有的帧皆为P帧
        for( int j = 1; j <= num_frames; j++ )
            frames[j]->i_type = X264_TYPE_P;
        reset_start = !keyframe + 1;
        num_bframes = 0;
    }

    /* Perform the actual macroblock tree analysis.
     * Don't go farther than the maximum keyframe interval; this helps in short GOPs. */
    if( h->param.rc.b_mb_tree )
        x264_macroblock_tree( h, &a, frames, X264_MIN(num_frames, h->param.i_keyint_max), keyframe );

    /* Enforce keyframe limit. */
    if( !h->param.b_intra_refresh )
        for( int i = keyint_limit+1; i <= num_frames; i += h->param.i_keyint_max )
        {
            //迫使为I帧
            frames[i]->i_type = X264_TYPE_I;
            reset_start = X264_MIN( reset_start, i+1 );
            if( h->param.b_open_gop && h->param.b_bluray_compat )
                while( IS_X264_TYPE_B( frames[i-1]->i_type ) )
                    i--;
        }

    if( vbv_lookahead )
        x264_vbv_lookahead( h, &a, frames, num_frames, keyframe );

    /* Restore frametypes for all frames that haven't actually been decided yet. */
    for( int j = reset_start; j <= num_frames; j++ )
        frames[j]->i_type = X264_TYPE_AUTO;

#if HAVE_OPENCL
    x264_opencl_slicetype_end( h );
#endif
}
```

通过源代码可以看出，x264_slicetype_analyse()分析了frames[]队列中的视频帧的帧类型。简单总结一下该函数的流程：

（1）如果frames[1]通过scenecut()判断为场景切换，设置为I帧，并且直接返回。

（2）如果i_bframe为0，即不使用B帧，则将所有帧都设置为P帧。

（3）如果i_bframe不为0，即使用B帧，则需要进行比较复杂的帧开销计算。这时候需要调用一帧图像开销的计算函数x264_slicetype_frame_cost()。

有关帧类型判断在代码中已经做了注释，不再详细记录，下文继续看一下x264_slicetype_frame_cost()函数。

x264_slicetype_frame_cost()

x264_slicetype_frame_cost()用于计算一帧图像的开销。该函数的定义位于encoder\slicetype.c，如下所示。

```cpp
//一帧图像的开销
//x264_slicetype_frame_cost(,,,p0,p1,b,)
// p0 b p1
static int x264_slicetype_frame_cost( x264_t *h, x264_mb_analysis_t *a,
                                      x264_frame_t **frames, int p0, int p1, int b,
                                      int b_intra_penalty )
{
    int i_score = 0;
    int do_search[2];
    const x264_weight_t *w = x264_weight_none;
    x264_frame_t *fenc = frames[b];

    /* Check whether we already evaluated this frame
     * If we have tried this frame as P, then we have also tried
     * the preceding frames as B. (is this still true?) */
    /* Also check that we already calculated the row SATDs for the current frame. */
    //如果已经计算过就不用算了
    if( fenc->i_cost_est[b-p0][p1-b] >= 0 && (!h->param.rc.i_vbv_buffer_size || fenc->i_row_satds[b-p0][p1-b][0] != -1) )
        i_score = fenc->i_cost_est[b-p0][p1-b];
    else
    {
        int dist_scale_factor = 128;

        /* For each list, check to see whether we have lowres motion-searched this reference frame before. */
        do_search[0] = b != p0 && fenc->lowres_mvs[0][b-p0-1][0][0] == 0x7FFF;
        do_search[1] = b != p1 && fenc->lowres_mvs[1][p1-b-1][0][0] == 0x7FFF;
        if( do_search[0] )
        {
            if( h->param.analyse.i_weighted_pred && b == p1 )
            {
                x264_emms();
                x264_weights_analyse( h, fenc, frames[p0], 1 );
                w = fenc->weight[0];
            }
            fenc->lowres_mvs[0][b-p0-1][0][0] = 0;
        }
        if( do_search[1] ) fenc->lowres_mvs[1][p1-b-1][0][0] = 0;

        if( p1 != p0 )
            dist_scale_factor = ( ((b-p0) << 8) + ((p1-p0) >> 1) ) / (p1-p0);

        int output_buf_size = h->mb.i_mb_height + (NUM_INTS + PAD_SIZE) * h->param.i_lookahead_threads;
        int *output_inter[X264_LOOKAHEAD_THREAD_MAX+1];
        int *output_intra[X264_LOOKAHEAD_THREAD_MAX+1];
        output_inter[0] = h->scratch_buffer2;
        output_intra[0] = output_inter[0] + output_buf_size;

#if HAVE_OPENCL
        if( h->param.b_opencl )
        {
            x264_opencl_lowres_init(h, fenc, a->i_lambda );
            if( do_search[0] )
            {
                x264_opencl_lowres_init( h, frames[p0], a->i_lambda );
                x264_opencl_motionsearch( h, frames, b, p0, 0, a->i_lambda, w );
            }
            if( do_search[1] )
            {
                x264_opencl_lowres_init( h, frames[p1], a->i_lambda );
                x264_opencl_motionsearch( h, frames, b, p1, 1, a->i_lambda, NULL );
            }
            if( b != p0 )
                x264_opencl_finalize_cost( h, a->i_lambda, frames, p0, p1, b, dist_scale_factor );
            x264_opencl_flush( h );

            i_score = fenc->i_cost_est[b-p0][p1-b];
        }
        else
#endif
        {
            if( h->param.i_lookahead_threads > 1 )
            {
                x264_slicetype_slice_t s[X264_LOOKAHEAD_THREAD_MAX];

```

```
            for( int i = 0; i < h->param.i_lookahead_threads; i++ )
            {
                x264_t *t = h->lookahead_thread[i];

                /* FIXME move this somewhere else */
                t->mb.i_me_method = h->mb.i_me_method;
                t->mb.i_subpel_refine = h->mb.i_subpel_refine;
                t->mb.b_chroma_me = h->mb.b_chroma_me;

                s[i] = (x264_slicetype_slice_t){ t, a, frames, p0, p1, b, dist_scale_factor, do_search, w,
                    output_inter[i], output_intra[i] };

                t->i_threadslice_start = ((h->mb.i_mb_height *  i    + h->param.i_lookahead_threads/2) / h->param.i_lookahead_threads);
                t->i_threadslice_end   = ((h->mb.i_mb_height * (i+1) + h->param.i_lookahead_threads/2) / h->param.i_lookahead_threads);

                int thread_height = t->i_threadslice_end - t->i_threadslice_start;
                int thread_output_size = thread_height + NUM_INTS;
                memset( output_inter[i], 0, thread_output_size * sizeof(int) );
                memset( output_intra[i], 0, thread_output_size * sizeof(int) );
                output_inter[i][NUM_ROWS] = output_intra[i][NUM_ROWS] = thread_height;

                output_inter[i+1] = output_inter[i] + thread_output_size + PAD_SIZE;
                output_intra[i+1] = output_intra[i] + thread_output_size + PAD_SIZE;

                x264_threadpool_run( h->lookaheadpool, (void*)x264_slicetype_slice_cost, &s[i] );
            }
            for( int i = 0; i < h->param.i_lookahead_threads; i++ )
                x264_threadpool_wait( h->lookaheadpool, &s[i] );
        }
        else
        {
            h->i_threadslice_start = 0;
            h->i_threadslice_end = h->mb.i_mb_height;
            memset( output_inter[0], 0, (output_buf_size - PAD_SIZE) * sizeof(int) );
            memset( output_intra[0], 0, (output_buf_size - PAD_SIZE) * sizeof(int) );
            output_inter[0][NUM_ROWS] = output_intra[0][NUM_ROWS] = h->mb.i_mb_height;
            //作为参数的结构体
            x264_slicetype_slice_t s = (x264_slicetype_slice_t){ h, a, frames, p0, p1, b, dist_scale_factor, do_search, w,
                output_inter[0], output_intra[0] };
            //一个slice的开销
            //输入输出参数都在s结构体中
            x264_slicetype_slice_cost( &s );
        }

        /* Sum up accumulators */
        if( b == p1 )
            fenc->i_intra_mbs[b-p0] = 0;
        if( !fenc->b_intra_calculated )
        {
            fenc->i_cost_est[0][0] = 0;
            fenc->i_cost_est_aq[0][0] = 0;
        }
        fenc->i_cost_est[b-p0][p1-b] = 0;
        fenc->i_cost_est_aq[b-p0][p1-b] = 0;

        int *row_satd_inter = fenc->i_row_satds[b-p0][p1-b];
        int *row_satd_intra = fenc->i_row_satds[0][0];
        for( int i = 0; i < h->param.i_lookahead_threads; i++ )
        {
            //累加output_inter[]或output_intra[]
            //这2个变量中存储了整帧的开销
            if( b == p1 )
                fenc->i_intra_mbs[b-p0] += output_inter[i][INTRA_MBS];
            if( !fenc->b_intra_calculated )
            {
                //帧内编码的代价
                fenc->i_cost_est[0][0] += output_intra[i][COST_EST];
                fenc->i_cost_est_aq[0][0] += output_intra[i][COST_EST_AQ];
            }

            //帧间编码的代价
            fenc->i_cost_est[b-p0][p1-b] += output_inter[i][COST_EST];
            fenc->i_cost_est_aq[b-p0][p1-b] += output_inter[i][COST_EST_AQ];

            if( h->param.rc.i_vbv_buffer_size )
            {
                int row_count = output_inter[i][NUM_ROWS];
                memcpy( row_satd_inter, output_inter[i] + NUM_INTS, row_count * sizeof(int) );
                if( !fenc->b_intra_calculated )
                    memcpy( row_satd_intra, output_intra[i] + NUM_INTS, row_count * sizeof(int) );
                row_satd_inter += row_count;
                row_satd_intra += row_count;
            }
        }
        //一帧的开销
        i_score = fenc->i_cost_est[b-p0][p1-b];
        if( b != p1 )//B帧
            i_score = (uint64_t)i_score * 100 / (120 + h->param.i_bframe_bias);
        else
```

```
                fenc->b_intra_calculated = 1;

            fenc->i_cost_est[b-p0][p1-b] = i_score;
            x264_emms();
        }
    }

    if( b_intra_penalty )
    {
        // arbitrary penalty for I-blocks after B-frames
        int nmb = NUM_MBS;
        i_score += (uint64_t)i_score * fenc->i_intra_mbs[b-p0] / (nmb * 8);
    }
    //返回一帧的开销值
    return i_score;
}
```

从源代码可以看出，x264_slicetype_analyse()调用了x264_slicetype_slice_cost()来计算一个slice的开销。

x264_slicetype_slice_cost()

x264_slicetype_slice_cost()用来计算一个slice的开销。该函数的定义位于encoder\slicetype.c，如下所示。

[cpp]

```
//一个slice的开销
static void x264_slicetype_slice_cost( x264_slicetype_slice_t *s )
{
    x264_t *h = s->h;

    /* Lowres lookahead goes backwards because the MVs are used as predictors in the main encode.
     * This considerably improves MV prediction overall. */

    /* The edge mbs seem to reduce the predictive quality of the
     * whole frame's score, but are needed for a spatial distribution. */
    int do_edges = h->param.rc.b_mb_tree || h->param.rc.i_vbv_buffer_size || h->mb.i_mb_width <= 2 || h->mb.i_mb_height <= 2;

    int start_y = X264_MIN( h->i_threadslice_end - 1, h->mb.i_mb_height - 2 + do_edges );
    int end_y = X264_MAX( h->i_threadslice_start, 1 - do_edges );
    int start_x = h->mb.i_mb_width - 2 + do_edges;
    int end_x = 1 - do_edges;

    //逐个计算每个MB的开销
    for( h->mb.i_mb_y = start_y; h->mb.i_mb_y >= end_y; h->mb.i_mb_y-- )
        for( h->mb.i_mb_x = start_x; h->mb.i_mb_x >= end_x; h->mb.i_mb_x-- )
            x264_slicetype_mb_cost( h, s->a, s->frames, s->p0, s->p1, s->b, s->dist_scale_factor,
                                    s->do_search, s->w, s->output_inter, s->output_intra );
}
```

从源代码可以看出，x264_slicetype_slice_cost()循环遍历了每一个宏块，针对每一个宏块调用了x264_slicetype_mb_cost()。

x264_slicetype_mb_cost()

x264_slicetype_mb_cost()用于计算一个宏块的编码代价。该函数的定义位于encoder\slicetype.c，如下所示。

[cpp]

```
//一个MB的开销
static void x264_slicetype_mb_cost( x264_t *h, x264_mb_analysis_t *a,
                                    x264_frame_t **frames, int p0, int p1, int b,
                                    int dist_scale_factor, int do_search[2], const x264_weight_t *w,
                                    int *output_inter, int *output_intra )
{
    x264_frame_t *fref0 = frames[p0];
    x264_frame_t *fref1 = frames[p1];
    x264_frame_t *fenc  = frames[b];
    const int b_bidir = (b < p1);
    const int i_mb_x = h->mb.i_mb_x;
    const int i_mb_y = h->mb.i_mb_y;
    const int i_mb_stride = h->mb.i_mb_width;
    const int i_mb_xy = i_mb_x + i_mb_y * i_mb_stride;
    const int i_stride = fenc->i_stride_lowres;
    const int i_pel_offset = 8 * (i_mb_x + i_mb_y * i_stride);
    const int i_bipred_weight = h->param.analyse.b_weighted_bipred ? 64 - (dist_scale_factor>>2) : 32;
    int16_t (*fenc_mvs[2])[2] = { &fenc->lowres_mvs[0][b-p0-1][i_mb_xy], &fenc->lowres_mvs[1][p1-b-1][i_mb_xy] };
    int (*fenc_costs[2]) = { &fenc->lowres_mv_costs[0][b-p0-1][i_mb_xy], &fenc->lowres_mv_costs[1][p1-b-1][i_mb_xy] };
    int b_frame_score_mb = (i_mb_x > 0 && i_mb_x < h->mb.i_mb_width - 1 &&
                            i_mb_y > 0 && i_mb_y < h->mb.i_mb_height - 1) ||
                            h->mb.i_mb_width <= 2 || h->mb.i_mb_height <= 2;

    ALIGNED_ARRAY_16( pixel, pix1,[9*FDEC_STRIDE] );
    pixel *pix2 = pix1+8;
    x264_me_t m[2];
    int i_bcost = COST_MAX;
    int list_used = 0;
    /* A small, arbitrary bias to avoid VBV problems caused by zero-residual lookahead blocks. */
```

```
    int lowres_penalty = 4;
    //计算只涉及一个分量
    h->mb.pic.p_fenc[0] = h->mb.pic.fenc_buf;
    //从低分辨率（1/2线性内插）图像中拷贝数据
    h->mc.copy[PIXEL_8x8]( h->mb.pic.p_fenc[0], FENC_STRIDE, &fenc->lowres[0][i_pel_offset], i_stride, 8 );

    if( p0 == p1 )
        goto lowres_intra_mb;

    // no need for h->mb.mv_min[]
    h->mb.mv_limit_fpel[0][0] = -8*h->mb.i_mb_x - 4;
    h->mb.mv_limit_fpel[1][0] = 8*( h->mb.i_mb_width - h->mb.i_mb_x - 1 ) + 4;
    h->mb.mv_min_spel[0] = 4*( h->mb.mv_limit_fpel[0][0] - 8 );
    h->mb.mv_max_spel[0] = 4*( h->mb.mv_limit_fpel[1][0] + 8 );
    if( h->mb.i_mb_x >= h->mb.i_mb_width - 2 )
    {
        h->mb.mv_limit_fpel[0][1] = -8*h->mb.i_mb_y - 4;
        h->mb.mv_limit_fpel[1][1] = 8*( h->mb.i_mb_height - h->mb.i_mb_y - 1 ) + 4;
        h->mb.mv_min_spel[1] = 4*( h->mb.mv_limit_fpel[0][1] - 8 );
        h->mb.mv_max_spel[1] = 4*( h->mb.mv_limit_fpel[1][1] + 8 );
    }

#define LOAD_HPELS_LUMA(dst, src) \
    { \
        (dst)[0] = &(src)[0][i_pel_offset]; \
        (dst)[1] = &(src)[1][i_pel_offset]; \
        (dst)[2] = &(src)[2][i_pel_offset]; \
        (dst)[3] = &(src)[3][i_pel_offset]; \
    }
#define LOAD_WPELS_LUMA(dst,src) \
    (dst) = &(src)[i_pel_offset];

#define CLIP_MV( mv ) \
    { \
        mv[0] = x264_clip3( mv[0], h->mb.mv_min_spel[0], h->mb.mv_max_spel[0] ); \
        mv[1] = x264_clip3( mv[1], h->mb.mv_min_spel[1], h->mb.mv_max_spel[1] ); \
    }
#define TRY_BIDIR( mv0, mv1, penalty ) \
    { \
        int i_cost; \
        if( h->param.analyse.i_subpel_refine <= 1 ) \
        { \
            int hpel_idx1 = (((mv0)[0]&2)>>1) + ((mv0)[1]&2); \
            int hpel_idx2 = (((mv1)[0]&2)>>1) + ((mv1)[1]&2); \
            pixel *src1 = m[0].p_fref[hpel_idx1] + ((mv0)[0]>>2) + ((mv0)[1]>>2) * m[0].i_stride[0]; \
            pixel *src2 = m[1].p_fref[hpel_idx2] + ((mv1)[0]>>2) + ((mv1)[1]>>2) * m[1].i_stride[0]; \
            h->mc.avg[PIXEL_8x8]( pix1, 16, src1, m[0].i_stride[0], src2, m[1].i_stride[0], i_bipred_weight ); \
        } \
        else \
        { \
            intptr_t stride1 = 16, stride2 = 16; \
            pixel *src1, *src2; \
            src1 = h->mc.get_ref( pix1, &stride1, m[0].p_fref, m[0].i_stride[0], \
                                  (mv0)[0], (mv0)[1], 8, 8, w ); \
            src2 = h->mc.get_ref( pix2, &stride2, m[1].p_fref, m[1].i_stride[0], \
                                  (mv1)[0], (mv1)[1], 8, 8, w ); \
            h->mc.avg[PIXEL_8x8]( pix1, 16, src1, stride1, src2, stride2, i_bipred_weight ); \
        } \
        i_cost = penalty * a->i_lambda + h->pixf.mbcmp[PIXEL_8x8]( \
                           m[0].p_fenc[0], FENC_STRIDE, pix1, 16 ); \
        COPY2_IF_LT( i_bcost, i_cost, list_used, 3 ); \
    }

    //帧间编码（后面还有帧内编码）

    //处理m[0]
    m[0].i_pixel = PIXEL_8x8;
    m[0].p_cost_mv = a->p_cost_mv;
    m[0].i_stride[0] = i_stride;
    m[0].p_fenc[0] = h->mb.pic.p_fenc[0];
    m[0].weight = w;
    m[0].i_ref = 0;
    //加载1/2插值像素点
    LOAD_HPELS_LUMA( m[0].p_fref, fref0->lowres );
    m[0].p_fref_w = m[0].p_fref[0];
    if( w[0].weightfn )
        LOAD_WPELS_LUMA( m[0].p_fref_w, fenc->weighted[0] );
    //双线预测，处理m[1]
    if( b_bidir )
    {
        int16_t *mvr = fref1->lowres_mvs[0][p1-p0-1][i_mb_xy];
        ALIGNED_ARRAY_8( int16_t, dmv,[2],[2] );

        m[1].i_pixel = PIXEL_8x8;
        m[1].p_cost_mv = a->p_cost_mv;
        m[1].i_stride[0] = i_stride;
        m[1].p_fenc[0] = h->mb.pic.p_fenc[0];
        m[1].i_ref = 0;
        m[1].weight = x264_weight_none;
        LOAD_HPELS_LUMA( m[1].p_fref, fref1->lowres );
        m[1].p_fref_w = m[1].p_fref[0];
```

```c

        dmv[0][0] = ( mvr[0] * dist_scale_factor + 128 ) >> 8;
        dmv[0][1] = ( mvr[1] * dist_scale_factor + 128 ) >> 8;
        dmv[1][0] = dmv[0][0] - mvr[0];
        dmv[1][1] = dmv[0][1] - mvr[1];
        CLIP_MV( dmv[0] );
        CLIP_MV( dmv[1] );
        if( h->param.analyse.i_subpel_refine <= 1 )
            M64( dmv ) &= ~0x0001000100010001ULL; /* mv & ~1 */

        //双向预测，其中包含了mc.avg[PIXEL_8x8]()
        TRY_BIDIR( dmv[0], dmv[1], 0 );
        if( M64( dmv ) )
        {
            int i_cost;
            h->mc.avg[PIXEL_8x8]( pix1, 16, m[0].p_fref[0], m[0].i_stride[0], m[1].p_fref[0], m[1].i_stride[0], i_bipred_weight );
            i_cost = h->pixf.mbcmp[PIXEL_8x8]( m[0].p_fenc[0], FENC_STRIDE, pix1, 16 );
            COPY2_IF_LT( i_bcost, i_cost, list_used, 3 );
        }
    }

    for( int l = 0; l < 1 + b_bidir; l++ )
    {
        if( do_search[l] )
        {
            int i_mvc = 0;
            int16_t (*fenc_mv)[2] = fenc_mvs[l];
            ALIGNED_4( int16_t mvc[4][2] );

            /* Reverse-order MV prediction. */
            M32( mvc[0] ) = 0;
            M32( mvc[2] ) = 0;
#define MVC(mv) { CP32( mvc[i_mvc], mv ); i_mvc++; }
            if( i_mb_x < h->mb.i_mb_width - 1 )
                MVC( fenc_mv[1] );
            if( i_mb_y < h->i_threadslice_end - 1 )
            {
                MVC( fenc_mv[i_mb_stride] );
                if( i_mb_x > 0 )
                    MVC( fenc_mv[i_mb_stride-1] );
                if( i_mb_x < h->mb.i_mb_width - 1 )
                    MVC( fenc_mv[i_mb_stride+1] );
            }
#undef MVC
            if( i_mvc <= 1 )
                CP32( m[l].mvp, mvc[0] );
            else
                x264_median_mv( m[l].mvp, mvc[0], mvc[1], mvc[2] );

            /* Fast skip for cases of near-zero residual.  Shortcut: don't bother except in the mv0 case,
             * since anything else is likely to have enough residual to not trigger the skip. */
            if( !M32( m[l].mvp ) )
            {
                m[l].cost = h->pixf.mbcmp[PIXEL_8x8]( m[l].p_fenc[0], FENC_STRIDE, m[l].p_fref[0], m[l].i_stride[0] );
                if( m[l].cost < 64 )
                {
                    M32( m[l].mv ) = 0;
                    goto skip_motionest;
                }
            }
            //运动搜索，开销存在m[l].cost中
            x264_me_search( h, &m[l], mvc, i_mvc );
            m[l].cost -= a->p_cost_mv[0]; // remove mvcost from skip mbs
            if( M32( m[l].mv ) )
                m[l].cost += 5 * a->i_lambda;

skip_motionest:
            CP32( fenc_mvs[l], m[l].mv );
            *fenc_costs[l] = m[l].cost;
        }
        else
        {
            CP32( m[l].mv, fenc_mvs[l] );
            m[l].cost = *fenc_costs[l];
        }
        //如果更小就拷贝
        //帧间编码开销，存储于i_bcost
        COPY2_IF_LT( i_bcost, m[l].cost, list_used, l+1 );
    }

    if( b_bidir && ( M32( m[0].mv ) || M32( m[1].mv ) ) )
        TRY_BIDIR( m[0].mv, m[1].mv, 5 );

lowres_intra_mb:
    //帧内编码
    if( !fenc->b_intra_calculated )
    {
        ALIGNED_ARRAY_16( pixel, edge,[36] );
        pixel *pix = &pix1[8+FDEC_STRIDE];
        pixel *src = &fenc->lowres[0][i_pel_offset];
        const int intra_penalty = 5 * a->i_lambda;
```

```
        int satds[3];
        int pixoff = 4 / sizeof(pixel);

        /* Avoid store forwarding stalls by writing larger chunks */
        memcpy( pix-FDEC_STRIDE, src-i_stride, 16 * sizeof(pixel) );
        for( int i = -1; i < 8; i++ )
            M32( &pix[i*FDEC_STRIDE-pixoff] ) = M32( &src[i*i_stride-pixoff] );

        //8x8块的SAD/SATD计算
        //x3打表计算了V，H，DC三种模式，开销存储在satds[3]数组的3个元素中
        h->pixf.intra_mbcmp_x3_8x8c( h->mb.pic.p_fenc[0], pix, satds );
        //帧内编码开销，存储于i_icost
        int i_icost = X264_MIN3( satds[0], satds[1], satds[2] );

        if( h->param.analyse.i_subpel_refine > 1 )
        {
            h->predict_8x8c[I_PRED_CHROMA_P]( pix );
            int satd = h->pixf.mbcmp[PIXEL_8x8]( pix, FDEC_STRIDE, h->mb.pic.p_fenc[0], FENC_STRIDE );
            i_icost = X264_MIN( i_icost, satd );
            h->predict_8x8_filter( pix, edge, ALL_NEIGHBORS, ALL_NEIGHBORS );
            for( int i = 3; i < 9; i++ )
            {
                h->predict_8x8[i]( pix, edge );
                satd = h->pixf.mbcmp[PIXEL_8x8]( pix, FDEC_STRIDE, h->mb.pic.p_fenc[0], FENC_STRIDE );
                i_icost = X264_MIN( i_icost, satd );
            }
        }

        i_icost += intra_penalty + lowres_penalty;
        //存一下
        fenc->i_intra_cost[i_mb_xy] = i_icost;
        int i_icost_aq = i_icost;
        if( h->param.rc.i_aq_mode )
            i_icost_aq = (i_icost_aq * fenc->i_inv_qscale_factor[i_mb_xy] + 128) >> 8;
        output_intra[ROW_SATD] += i_icost_aq;
        if( b_frame_score_mb )
        {
            //累加。[COST_EST]用于整帧的开销计算
            output_intra[COST_EST] += i_icost;
            output_intra[COST_EST_AQ] += i_icost_aq;
        }
    }
    i_bcost += lowres_penalty;

    /* forbid intra-mbs in B-frames, because it's rare and not worth checking */
    /* FIXME: Should we still forbid them now that we cache intra scores? */
    if( !b_bidir )
    {
        int i_icost = fenc->i_intra_cost[i_mb_xy];
        //帧内开销比帧间更小，b_intra就会取1
        int b_intra = i_icost < i_bcost;
        if( b_intra )
        {
            //赋值给i_bcost
            i_bcost = i_icost;
            list_used = 0;
        }
        if( b_frame_score_mb )
            output_inter[INTRA_MBS] += b_intra;//[INTRA_MBS]统计有多少个帧内模式的宏块
    }

    /* In an I-frame, we've already added the results above in the intra section. */
    if( p0 != p1 )
    {
        int i_bcost_aq = i_bcost;
        if( h->param.rc.i_aq_mode )
            i_bcost_aq = (i_bcost_aq * fenc->i_inv_qscale_factor[i_mb_xy] + 128) >> 8;
        output_inter[ROW_SATD] += i_bcost_aq;
        if( b_frame_score_mb )
        {
            /* Don't use AQ-weighted costs for slicetype decision, only for ratecontrol. */
            //累加。[COST_EST]用于整帧的开销计算
            output_inter[COST_EST] += i_bcost;
            output_inter[COST_EST_AQ] += i_bcost_aq;
        }
    }
    //存储开销i_bcost
    fenc->lowres_costs[b-p0][p1-b][i_mb_xy] = X264_MIN( i_bcost, LOWRES_COST_MASK ) + (list_used << LOWRES_COST_SHIFT);
}
#undef TRY_BIDIR
```

宏块开销这里在源代码上写了比较详细的注释，不再详细记录。在这里有一点需要注意：处理的图像是经过1/2线性差值的“低分辨率（lowres）”图片（这样速度更快？），而其中宏块的大小也是以8x8而不是16x16为单位的。

x264_frame_shift()

x264_frame_shift()用于从队列头部取出1帧。该函数的定义位于common\frame.c，如下所示。

```cpp
//从队列的头部取出一帧
x264_frame_t *x264_frame_shift( x264_frame_t **list )
{
    x264_frame_t *frame = list[0];
    int i;
    for( i = 0; list[i]; i++ )
        list[i] = list[i+1];
    assert(frame);
    return frame;
}
```

从源代码可以看出，x264_frame_shift()取出了list[0]并且作为返回值返回。

x264_reference_update()

x264_reference_update()用于更新参考帧队列（将重建帧fdec加入参考帧队列）。该函数的定义位于encoder\encoder.c，如下所示。

```cpp
//更新参考帧队列，若为非参考B帧则不更新
//重建帧移植参考帧列表，新建一个重建帧
static inline int x264_reference_update( x264_t *h )
{
    //如果不是被参考的帧
    if( !h->fdec->b_kept_as_ref )
    {
        if( h->i_thread_frames > 1 )
        {
            x264_frame_push_unused( h, h->fdec );
            h->fdec = x264_frame_pop_unused( h, 1 );
            if( !h->fdec )
                return -1;
        }
        return 0;
    }

    /* apply mmco from previous frame. */
    for( int i = 0; i < h->sh.i_mmco_command_count; i++ )
        for( int j = 0; h->frames.reference[j]; j++ )
            if( h->frames.reference[j]->i_poc == h->sh.mmco[i].i_poc )
                x264_frame_push_unused( h, x264_frame_shift( &h->frames.reference[j] ) );

    /* move frame in the buffer */
    //重建帧加入参考帧列表
    x264_frame_push( h->frames.reference, h->fdec );
    //列表满了，则要移除1帧
    if( h->frames.reference[h->sps->i_num_ref_frames] )
        x264_frame_push_unused( h, x264_frame_shift( h->frames.reference ) );
    //重新初始化重建帧fdec
    h->fdec = x264_frame_pop_unused( h, 1 );
    if( !h->fdec )
        return -1;
    return 0;
}
```

从源代码可以看出，如果重建帧fdec是不被参考的B帧，则直接返回；如果fdec是被参考的帧，则会调用x264_frame_push()将该帧加入frames.reference[]队列的尾部。如果frames.reference[]已经满了，则会调用x264_frame_shift()和x264_frame_push_unused()将frames.reference[]队列头部的帧移动到frames.unused[]队列。最后函数还会调用x264_frame_pop_unused()获取一个新的重建帧fdec。

x264_reference_reset()

如果编码帧为IDR帧，就会调用x264_reference_reset()函数清空参考帧列表。该函数定义位于encoder\encoder.c，如下所示。

```cpp
//清空所有参考帧
static inline void x264_reference_reset( x264_t *h )
{
    //把frames.reference[]中所有帧移动到frames.unused[]
    while( h->frames.reference[0] )
        x264_frame_push_unused( h, x264_frame_pop( h->frames.reference ) );
    h->fdec->i_poc =
    h->fenc->i_poc = 0;
}
```

从源代码可以看出，x264_reference_reset()中调用x264_frame_pop()和x264_frame_push_unused()将frames.reference[]队列中的帧移动到frames.unused[]队列中。

x264_slice_init()

x264_slice_init()用于创建Slice Header，初始化其中的信息。该函数的定义位于encoder\encoder.c，如下所示。

[cpp]

```cpp
//创建Slice Header
static inline void x264_slice_init( x264_t *h, int i_nal_type, int i_global_qp )
{
    /* ------------------------ Create slice header  ----------------------- */
    if( i_nal_type == NAL_SLICE_IDR )
    {
        //I帧

        //对x264_slice_header_t进行赋值
        x264_slice_header_init( h, &h->sh, h->sps, h->pps, h->i_idr_pic_id, h->i_frame_num, i_global_qp );

        /* alternate id */
        if( h->param.i_avcintra_class )
        {
            switch( h->i_idr_pic_id )
            {
                case 5:
                    h->i_idr_pic_id = 3;
                    break;
                case 3:
                    h->i_idr_pic_id = 4;
                    break;
                case 4:
                default:
                    h->i_idr_pic_id = 5;
                    break;
            }
        }
        else
            h->i_idr_pic_id ^= 1;
    }
    else
    {
        //非IDR帧
        x264_slice_header_init( h, &h->sh, h->sps, h->pps, -1, h->i_frame_num, i_global_qp );
        //参考帧列表
        h->sh.i_num_ref_idx_l0_active = h->i_ref[0] <= 0 ? 1 : h->i_ref[0];
        h->sh.i_num_ref_idx_l1_active = h->i_ref[1] <= 0 ? 1 : h->i_ref[1];
        if( h->sh.i_num_ref_idx_l0_active != h->pps->i_num_ref_idx_l0_default_active ||
            (h->sh.i_type == SLICE_TYPE_B && h->sh.i_num_ref_idx_l1_active != h->pps->i_num_ref_idx_l1_default_active) )
        {
            h->sh.b_num_ref_idx_override = 1;
        }
    }

    if( h->fenc->i_type == X264_TYPE_BREF && h->param.b_bluray_compat && h->sh.i_mmco_command_count )
    {
        h->b_sh_backup = 1;
        h->sh_backup = h->sh;
    }

    h->fdec->i_frame_num = h->sh.i_frame_num;

    if( h->sps->i_poc_type == 0 )
    {
        h->sh.i_poc = h->fdec->i_poc;
        if( PARAM_INTERLACED )
        {
            h->sh.i_delta_poc_bottom = h->param.b_tff ? 1 : -1;
            h->sh.i_poc += h->sh.i_delta_poc_bottom == -1;
        }
        else
            h->sh.i_delta_poc_bottom = 0;
        h->fdec->i_delta_poc[0] = h->sh.i_delta_poc_bottom == -1;
        h->fdec->i_delta_poc[1] = h->sh.i_delta_poc_bottom ==  1;
    }
    else
    {
        /* Nothing to do ? */
    }
    //主要对mb结构体赋初值
    x264_macroblock_slice_init( h );
}
```

从源代码可以看出，x264_slice_init()调用x264_slice_header_init()完成了Slice Header “通用”的初始化工作，然后根据帧类型的不同，做了一些特殊参数的设置。下面看一下x264_slice_header_init()。

x264_slice_header_init()

x264_slice_header_init()用于对Slice Header进行初始化工作。该函数的定义如下所示。

```cpp
/* Fill "default" values */
//对x264_slice_header_t进行赋值
static void x264_slice_header_init( x264_t *h, x264_slice_header_t *sh,
                                    x264_sps_t *sps, x264_pps_t *pps,
                                    int i_idr_pic_id, int i_frame, int i_qp )
{
    x264_param_t *param = &h->param;

    /* First we fill all fields */
    sh->sps = sps;
    sh->pps = pps;

    sh->i_first_mb  = 0;
    sh->i_last_mb   = h->mb.i_mb_count - 1;
    sh->i_pps_id    = pps->i_id;

    sh->i_frame_num = i_frame;

    sh->b_mbaff = PARAM_INTERLACED;
    sh->b_field_pic = 0;    /* no field support for now */
    sh->b_bottom_field = 0; /* not yet used */

    sh->i_idr_pic_id = i_idr_pic_id;

    /* poc stuff, fixed later */
    sh->i_poc = 0;
    sh->i_delta_poc_bottom = 0;
    sh->i_delta_poc[0] = 0;
    sh->i_delta_poc[1] = 0;

    sh->i_redundant_pic_cnt = 0;

    h->mb.b_direct_auto_write = h->param.analyse.i_direct_mv_pred == X264_DIRECT_PRED_AUTO
                                && h->param.i_bframe
                                && ( h->param.rc.b_stat_write || !h->param.rc.b_stat_read );

    if( !h->mb.b_direct_auto_read && sh->i_type == SLICE_TYPE_B )
    {
        if( h->fref[1][0]->i_poc_l0ref0 == h->fref[0][0]->i_poc )
        {
            if( h->mb.b_direct_auto_write )
                sh->b_direct_spatial_mv_pred = ( h->stat.i_direct_score[1] > h->stat.i_direct_score[0] );
            else
                sh->b_direct_spatial_mv_pred = ( param->analyse.i_direct_mv_pred == X264_DIRECT_PRED_SPATIAL );
        }
        else
        {
            h->mb.b_direct_auto_write = 0;
            sh->b_direct_spatial_mv_pred = 1;
        }
    }
    /* else b_direct_spatial_mv_pred was read from the 2pass statsfile */

    sh->b_num_ref_idx_override = 0;
    sh->i_num_ref_idx_l0_active = 1;
    sh->i_num_ref_idx_l1_active = 1;

    sh->b_ref_pic_list_reordering[0] = h->b_ref_reorder[0];
    sh->b_ref_pic_list_reordering[1] = h->b_ref_reorder[1];

    /* If the ref list isn't in the default order, construct reordering header */
    for( int list = 0; list < 2; list++ )
    {
        if( sh->b_ref_pic_list_reordering[list] )
        {
            int pred_frame_num = i_frame;
            for( int i = 0; i < h->i_ref[list]; i++ )
            {
                int diff = h->fref[list][i]->i_frame_num - pred_frame_num;
                sh->ref_pic_list_order[list][i].idc = ( diff > 0 );
                sh->ref_pic_list_order[list][i].arg = (abs(diff) - 1) & ((1 << sps->i_log2_max_frame_num) - 1);
                pred_frame_num = h->fref[list][i]->i_frame_num;
            }
        }
    }

    sh->i_cabac_init_idc = param->i_cabac_init_idc;

    sh->i_qp = SPEC_QP(i_qp);
    sh->i_qp_delta = sh->i_qp - pps->i_pic_init_qp;
    sh->b_sp_for_swidth = 0;
    sh->i_qs_delta = 0;

    int deblock_thresh = i_qp + 2 * X264_MIN(param->i_deblocking_filter_alphac0, param->i_deblocking_filter_beta);
    /* If effective qp <= 15, deblocking would have no effect anyway */
    if( param->b_deblocking_filter && (h->mb.b_variable_qp || 15 < deblock_thresh ) )
        sh->i_disable_deblocking_filter_idc = param->b_sliced_threads ? 2 : 0;
```

```cpp
    else
        sh->i_disable_deblocking_filter_idc = 1;
    sh->i_alpha_c0_offset = param->i_deblocking_filter_alphac0 << 1;
    sh->i_beta_offset = param->i_deblocking_filter_beta << 1;
}
```

可以看出x264_slice_header_init()对x264_slice_header_t结构体的成员变量进行了赋值。

x264_slices_write()

编码数据（最关键的步骤）。其中调用了x264_slice_write()完成了编码的工作（注意“x264_slices_write()”和“x264_slice_write()”名字差了一个“s”）。

[cpp]

```cpp
//真正的编码——编码1个图像帧
//注意“slice”后面有一个“s”
//它其中又调用了一个x264_slice_write()
//这一点要区分开
static void *x264_slices_write( x264_t *h )
{
    int i_slice_num = 0;
    int last_thread_mb = h->sh.i_last_mb;

    /* init stats */
    memset( &h->stat.frame, 0, sizeof(h->stat.frame) );
    h->mb.b_reencode_mb = 0;
    //循环每一个slice（一幅图像可以由多个Slice构成）
    while( h->sh.i_first_mb + SLICE_MBAFF*h->mb.i_mb_stride <= last_thread_mb )
    {
        h->sh.i_last_mb = last_thread_mb;
        if( !i_slice_num || !x264_frame_new_slice( h, h->fdec ) )
        {
            if( h->param.i_slice_max_mbs )
            {
                if( SLICE_MBAFF )
                {
                    // convert first to mbaff form, add slice-max-mbs, then convert back to normal form
                    int last_mbaff = 2*(h->sh.i_first_mb % h->mb.i_mb_width)
                        + h->mb.i_mb_width*(h->sh.i_first_mb / h->mb.i_mb_width)
                        + h->param.i_slice_max_mbs - 1;
                    int last_x = (last_mbaff % (2*h->mb.i_mb_width))/2;
                    int last_y = (last_mbaff / (2*h->mb.i_mb_width))*2 + 1;
                    h->sh.i_last_mb = last_x + h->mb.i_mb_stride*last_y;
                }
                else
                {
                    h->sh.i_last_mb = h->sh.i_first_mb + h->param.i_slice_max_mbs - 1;
                    if( h->sh.i_last_mb < last_thread_mb && last_thread_mb - h->sh.i_last_mb < h->param.i_slice_min_mbs )
                        h->sh.i_last_mb = last_thread_mb - h->param.i_slice_min_mbs;
                }
                i_slice_num++;
            }
            else if( h->param.i_slice_count && !h->param.b_sliced_threads )
            {
                int height = h->mb.i_mb_height >> PARAM_INTERLACED;
                int width = h->mb.i_mb_width << PARAM_INTERLACED;
                i_slice_num++;
                h->sh.i_last_mb = (height * i_slice_num + h->param.i_slice_count/2) / h->param.i_slice_count * width - 1;
            }
        }
        h->sh.i_last_mb = X264_MIN( h->sh.i_last_mb, last_thread_mb );
        //真正的编码——编码1个Slice
        //x264_stack_align()应该是平台优化过程中内存对齐的工作
        //实际上就是调用x264_slice_write()
        if( x264_stack_align( x264_slice_write, h ) )
            goto fail;
        //注意这里对i_first_mb进行了赋值
        h->sh.i_first_mb = h->sh.i_last_mb + 1;
        // if i_first_mb is not the last mb in a row then go to the next mb in MBAFF order
        if( SLICE_MBAFF && h->sh.i_first_mb % h->mb.i_mb_width )
            h->sh.i_first_mb -= h->mb.i_mb_stride;
    }

    return (void *)0;

fail:
    /* Tell other threads we're done, so they wouldn't wait for it */
    if( h->param.b_sliced_threads )
        x264_threadslice_cond_broadcast( h, 2 );
    return (void *)-1;
}
```

在这里需要注意，x264_slices_write()调用了x264_slice_write()。其中x264_slices_write()的单位为帧，而x264_slice_write()的单位为Slice。最常见的情况下一个帧里面只有一个Slice，但是也有可能一个帧里面有多个Slice。

x264_slice_write()

x264_slice_write()是完成编码工作的函数。该函数中包含了去块效应滤波，运动估计，宏块编码，熵编码等模块，它的调用结构大致如下图所示。

本文暂不分析x264_slice_write()函数。从下一篇文章开始将会对该函数进行详细的分析。

x264_encoder_frame_end()

x264_encoder_frame_end()用于在编码结束后做一些后续处理，例如封装NALU（加上起始码），释放一些中间变量，记录一些统计信息等。该函数的定义位于encoder\encoder.c，如下所示。

[cpp]

```cpp
//结束的时候做一些处理，记录一些统计信息
//pp_nal：输出的NALU
//pic_out：输出的重建帧
static int x264_encoder_frame_end( x264_t *h, x264_t *thread_current,
                                   x264_nal_t **pp_nal, int *pi_nal,
                                   x264_picture_t *pic_out )
{
    char psz_message[80];

    if( !h->param.b_sliced_threads && h->b_thread_active )
    {
        h->b_thread_active = 0;
        if( (intptr_t)x264_threadpool_wait( h->threadpool, h ) )
            return -1;
    }
    if( !h->out.i_nal )
    {
        pic_out->i_type = X264_TYPE_AUTO;
        return 0;
    }

    x264_emms();

    /* generate buffering period sei and insert it into place */
    if( h->i_thread_frames > 1 && h->fenc->b_keyframe && h->sps->vui.b_nal_hrd_parameters_present )
    {
        x264_hrd_fullness( h );
        x264_nal_start( h, NAL_SEI, NAL_PRIORITY_DISPOSABLE );
        x264_sei_buffering_period_write( h, &h->out.bs );
        if( x264_nal_end( h ) )
           return -1;
        /* buffering period sei must follow AUD, SPS and PPS and precede all other SEIs */
        int idx = 0;
        while( h->out.nal[idx].i_type == NAL_AUD ||
               h->out.nal[idx].i_type == NAL_SPS ||
               h->out.nal[idx].i_type == NAL_PPS )
            idx++;
        x264_nal_t nal_tmp = h->out.nal[h->out.i_nal-1];
        memmove( &h->out.nal[idx+1], &h->out.nal[idx], (h->out.i_nal-idx-1)*sizeof(x264_nal_t) );
        h->out.nal[idx] = nal_tmp;
    }
    //封装一帧数据对应的NALU.
    //例如给NALU添加起始码0x00000001
    int frame_size = x264_encoder_encapsulate_nals( h, 0 );
    if( frame_size < 0 )
        return -1;

    /* Set output picture properties */
    //pic_out为x264_picture_t类型结构体。是libx264对外的结构体
    //fenc,fdec是x264_frame_t类型结构体。是libx264的内部结构体
    pic_out->i_type = h->fenc->i_type;

    pic_out->b_keyframe = h->fenc->b_keyframe;
    pic_out->i_pic_struct = h->fenc->i_pic_struct;

    pic_out->i_pts = h->fdec->i_pts;
    pic_out->i_dts = h->fdec->i_dts;

    if( pic_out->i_pts < pic_out->i_dts )
        x264_log( h, X264_LOG_WARNING, "invalid DTS: PTS is less than DTS\n" );

    pic_out->opaque = h->fenc->opaque;

    pic_out->img.i_csp = h->fdec->i_csp;
#if HIGH_BIT_DEPTH
    pic_out->img.i_csp |= X264_CSP_HIGH_DEPTH;
#endif
    pic_out->img.i_plane = h->fdec->i_plane;
    //图像数据
    for( int i = 0; i < pic_out->img.i_plane; i++ )
    {
        pic_out->img.i_stride[i] = h->fdec->i_stride[i] * sizeof(pixel);
```

```c
        pic_out->img.plane[i] = (uint8_t*)h->fdec->plane[i];
    }
    //回收用过的编码帧fenc
    x264_frame_push_unused( thread_current, h->fenc );

    /* ---------------------- Update encoder state ------------------------- */

    /* update rc */
    int filler = 0;
    if( x264_ratecontrol_end( h, frame_size * 8, &filler ) < 0 )
        return -1;

    pic_out->hrd_timing = h->fenc->hrd_timing;
    pic_out->prop.f_crf_avg = h->fdec->f_crf_avg;

    /* Filler in AVC-Intra mode is written as zero bytes to the last slice
     * We don't know the size of the last slice until encapsulation so we add filler to the encapsulated NAL */
    if( h->param.i_avcintra_class )
    {
        x264_t *h0 = h->thread[0];
        int ret = x264_check_encapsulated_buffer( h, h0, h->out.i_nal, frame_size, frame_size + filler );
        if( ret < 0 )
            return -1;
        memset( h->out.nal[0].p_payload + frame_size, 0, filler );
        h->out.nal[h->out.i_nal-1].i_payload += filler;
        h->out.nal[h->out.i_nal-1].i_padding = filler;
        frame_size += filler;
    }
    else
    {
        while( filler > 0 )
        {
            int f, overhead;
            overhead = (FILLER_OVERHEAD - h->param.b_annexb);
            if( h->param.i_slice_max_size && filler > h->param.i_slice_max_size )
            {
                int next_size = filler - h->param.i_slice_max_size;
                int overflow = X264_MAX( overhead - next_size, 0 );
                f = h->param.i_slice_max_size - overhead - overflow;
            }
            else
                f = X264_MAX( 0, filler - overhead );

            if( x264_bitstream_check_buffer_filler( h, f ) )
                return -1;
            x264_nal_start( h, NAL_FILLER, NAL_PRIORITY_DISPOSABLE );
            x264_filler_write( h, &h->out.bs, f );
            if( x264_nal_end( h ) )
                return -1;
            int total_size = x264_encoder_encapsulate_nals( h, h->out.i_nal-1 );
            if( total_size < 0 )
                return -1;
            frame_size += total_size;
            filler -= total_size;
        }
    }

    /* End bitstream, set output  */
    *pi_nal = h->out.i_nal;
    *pp_nal = h->out.nal;

    h->out.i_nal = 0;

    x264_noise_reduction_update( h );

    /* ---------------------- Compute/Print statistics --------------------- */
    x264_thread_sync_stat( h, h->thread[0] );

    /* Slice stat */
    //stat中存储了统计信息
    //帧数+1 （根据类型）
    h->stat.i_frame_count[h->sh.i_type]++;
    //帧大小
    h->stat.i_frame_size[h->sh.i_type] += frame_size;
    h->stat.f_frame_qp[h->sh.i_type] += h->fdec->f_qp_avg_aq;
    //统计MB个数，把不同类型的累加起来
    for( int i = 0; i < X264_MBTYPE_MAX; i++ )
        h->stat.i_mb_count[h->sh.i_type][i] += h->stat.frame.i_mb_count[i];
    for( int i = 0; i < X264_PARTTYPE_MAX; i++ )
        h->stat.i_mb_partition[h->sh.i_type][i] += h->stat.frame.i_mb_partition[i];
    for( int i = 0; i < 2; i++ )
        h->stat.i_mb_count_8x8dct[i] += h->stat.frame.i_mb_count_8x8dct[i];
    for( int i = 0; i < 6; i++ )
        h->stat.i_mb_cbp[i] += h->stat.frame.i_mb_cbp[i];
    for( int i = 0; i < 4; i++ )
        for( int j = 0; j < 13; j++ )
            h->stat.i_mb_pred_mode[i][j] += h->stat.frame.i_mb_pred_mode[i][j];
    if( h->sh.i_type != SLICE_TYPE_I )
        for( int i_list = 0; i_list < 2; i_list++ )
            for( int i = 0; i < X264_REF_MAX*2; i++ )
                h->stat.i_mb_count_ref[h->sh.i_type][i_list][i] += h->stat.frame.i_mb_count_ref[i_list][i];
```

```
    for( int i = 0; i < 3; i++ )
        h->stat.i_mb_field[i] += h->stat.frame.i_mb_field[i];
    if( h->sh.i_type == SLICE_TYPE_P && h->param.analyse.i_weighted_pred >= X264_WEIGHTP_SIMPLE )
    {
        h->stat.i_wpred[0] += !!h->sh.weight[0][0].weightfn;
        h->stat.i_wpred[1] += !!h->sh.weight[0][1].weightfn || !!h->sh.weight[0][2].weightfn;
    }
    if( h->sh.i_type == SLICE_TYPE_B )
    {
        h->stat.i_direct_frames[ h->sh.b_direct_spatial_mv_pred ] ++;
        if( h->mb.b_direct_auto_write )
        {
            //FIXME somewhat arbitrary time constants
            if( h->stat.i_direct_score[0] + h->stat.i_direct_score[1] > h->mb.i_mb_count )
                for( int i = 0; i < 2; i++ )
                    h->stat.i_direct_score[i] = h->stat.i_direct_score[i] * 9/10;
            for( int i = 0; i < 2; i++ )
                h->stat.i_direct_score[i] += h->stat.frame.i_direct_score[i];
        }
    }
    else
        h->stat.i_consecutive_bframes[h->fenc->i_bframes]++;

    psz_message[0] = '\0';
    double dur = h->fenc->f_duration;
    h->stat.f_frame_duration[h->sh.i_type] += dur;

    //需要计算PSNR
    if( h->param.analyse.b_psnr )
    {
        //SSD（Sum of Squared Difference）即差值的平方和
        int64_t ssd[3] =
        {
            h->stat.frame.i_ssd[0],
            h->stat.frame.i_ssd[1],
            h->stat.frame.i_ssd[2],
        };
        int luma_size = h->param.i_width * h->param.i_height;
        int chroma_size = CHROMA_SIZE( luma_size );

        //SSD是已经在“滤波”环节计算过的
        //SSD简单换算成PSNR，调用x264_psnr()
        pic_out->prop.f_psnr[0] = x264_psnr( ssd[0], luma_size );
        pic_out->prop.f_psnr[1] = x264_psnr( ssd[1], chroma_size );
        pic_out->prop.f_psnr[2] = x264_psnr( ssd[2], chroma_size );
        //平均值
        pic_out->prop.f_psnr_avg = x264_psnr( ssd[0] + ssd[1] + ssd[2], luma_size + chroma_size*2 );
        //mean系列的需要累加
        h->stat.f_ssd_global[h->sh.i_type]   += dur * (ssd[0] + ssd[1] + ssd[2]);
        h->stat.f_psnr_average[h->sh.i_type] += dur * pic_out->prop.f_psnr_avg;
        h->stat.f_psnr_mean_y[h->sh.i_type]  += dur * pic_out->prop.f_psnr[0];
        h->stat.f_psnr_mean_u[h->sh.i_type]  += dur * pic_out->prop.f_psnr[1];
        h->stat.f_psnr_mean_v[h->sh.i_type]  += dur * pic_out->prop.f_psnr[2];

        snprintf( psz_message, 80, " PSNR Y:%5.2f U:%5.2f V:%5.2f", pic_out->prop.f_psnr[0],
                                                                   pic_out->prop.f_psnr[1],
                                                                   pic_out->prop.f_psnr[2] );
    }

    //需要计算SSIM
    if( h->param.analyse.b_ssim )
    {
        //SSIM是已经在“滤波”环节计算过的
        pic_out->prop.f_ssim = h->stat.frame.f_ssim / h->stat.frame.i_ssim_cnt;
        //mean系列的需要累加
        h->stat.f_ssim_mean_y[h->sh.i_type] += pic_out->prop.f_ssim * dur;
        snprintf( psz_message + strlen(psz_message), 80 - strlen(psz_message),
                  " SSIM Y:%.5f", pic_out->prop.f_ssim );
    }
    psz_message[79] = '\0';
    //Debug时候输出
    x264_log( h, X264_LOG_DEBUG,
                  "frame=%4d QP=%.2f NAL=%d Slice:%c Poc:%-3d I:%-4d P:%-4d SKIP:%-4d size=%d bytes%s\n",
              h->i_frame,
              h->fdec->f_qp_avg_aq,
              h->i_nal_ref_idc,
              h->sh.i_type == SLICE_TYPE_I ? 'I' : (h->sh.i_type == SLICE_TYPE_P ? 'P' : 'B' ),
              h->fdec->i_poc,
              h->stat.frame.i_mb_count_i,
              h->stat.frame.i_mb_count_p,
              h->stat.frame.i_mb_count_skip,
              frame_size,
              psz_message );

    // keep stats all in one place
    x264_thread_sync_stat( h->thread[0], h );
    // for the use of the next frame
    x264_thread_sync_stat( thread_current, h );

#ifdef DEBUG_MB_TYPE
{
```

```
    static const char mb_chars[] = { 'i', 'i', 'I', 'C', 'P', '8', 'S',
        'D', '<', 'X', 'B', 'X', '>', 'B', 'B', 'B', 'B', '8', 'S' };
    for( int mb_xy = 0; mb_xy < h->mb.i_mb_width * h->mb.i_mb_height; mb_xy++ )
    {
        if( h->mb.type[mb_xy] < X264_MBTYPE_MAX && h->mb.type[mb_xy] >= 0 )
            fprintf( stderr, "%c ", mb_chars[ h->mb.type[mb_xy] ] );
        else
            fprintf( stderr, "? " );

        if( (mb_xy+1) % h->mb.i_mb_width == 0 )
            fprintf( stderr, "\n" );
    }
}
#endif

    /* Remove duplicates, must be done near the end as breaks h->fref0 array
     * by freeing some of its pointers. */
    for( int i = 0; i < h->i_ref[0]; i++ )
        if( h->fref[0][i] && h->fref[0][i]->b_duplicate )
        {
            x264_frame_push_blank_unused( h, h->fref[0][i] );
            h->fref[0][i] = 0;
        }

    if( h->param.psz_dump_yuv )
        x264_frame_dump( h );
    x264_emms();

    return frame_size;
}
```

从源代码可以看出，x264_encoder_frame_end()中大部分代码用于把统计信息记录到x264_t的stat中。此外做了一些后续处理：调用了x264_encoder_encapsulate_nals()封装NALU（添加起始码），调用x264_frame_push_unused()将fenc重新放回frames.unused[]队列，并且调用x264_ratecontrol_end()结束码率控制。

x264_encoder_encapsulate_nals()

x264_encoder_encapsulate_nals()用于封装一帧数据对应的NALU，其代码如下所示。

[cpp]

```cpp
//封装一帧数据对应的NALU.
//例如给NALU添加起始码0x00000001
static int x264_encoder_encapsulate_nals( x264_t *h, int start )
{
    x264_t *h0 = h->thread[0];
    int nal_size = 0, previous_nal_size = 0;

    if( h->param.nalu_process )
    {
        for( int i = start; i < h->out.i_nal; i++ )
            nal_size += h->out.nal[i].i_payload;
        return nal_size;
    }

    for( int i = 0; i < start; i++ )
        previous_nal_size += h->out.nal[i].i_payload;

    for( int i = start; i < h->out.i_nal; i++ )
        nal_size += h->out.nal[i].i_payload;

    /* Worst-case NAL unit escaping: reallocate the buffer if it's too small. */
    int necessary_size = previous_nal_size + nal_size * 3/2 + h->out.i_nal * 4 + 4 + 64;
    for( int i = start; i < h->out.i_nal; i++ )
        necessary_size += h->out.nal[i].i_padding;
    if( x264_check_encapsulated_buffer( h, h0, start, previous_nal_size, necessary_size ) )
        return -1;

    uint8_t *nal_buffer = h0->nal_buffer + previous_nal_size;

    //一个一个NALU处理
    for( int i = start; i < h->out.i_nal; i++ )
    {
        int old_payload_len = h->out.nal[i].i_payload;
        h->out.nal[i].b_long_startcode = !i || h->out.nal[i].i_type == NAL_SPS || h->out.nal[i].i_type == NAL_PPS ||
                                         h->param.i_avcintra_class;
        //添加起始码
        x264_nal_encode( h, nal_buffer, &h->out.nal[i] );
        nal_buffer += h->out.nal[i].i_payload;
        if( h->param.i_avcintra_class )
        {
            h->out.nal[i].i_padding -= h->out.nal[i].i_payload - (old_payload_len + NALU_OVERHEAD);
            if( h->out.nal[i].i_padding > 0 )
            {
                memset( nal_buffer, 0, h->out.nal[i].i_padding );
                nal_buffer += h->out.nal[i].i_padding;
                h->out.nal[i].i_payload += h->out.nal[i].i_padding;
            }
            h->out.nal[i].i_padding = X264_MAX( h->out.nal[i].i_padding, 0 );
        }
    }

    x264_emms();

    return nal_buffer - (h0->nal_buffer + previous_nal_size);
}
```

从源代码中可以看出，x264_encoder_encapsulate_nals()调用了另外一个函数x264_nal_encode()逐个给一帧数据中的各个NALU添加起始码以及NALU Header等。

x264_nal_encode()

x264_nal_encode()用于给NALU添加起始码以及NALU Header等。该函数的定义位于common\bitstream.c，如下所示。

[cpp]

```cpp
/*****************************************************************************
 * x264_nal_encode:
 *****************************************************************************/
//添加起始码
void x264_nal_encode( x264_t *h, uint8_t *dst, x264_nal_t *nal )
{
    uint8_t *src = nal->p_payload;
    uint8_t *end = nal->p_payload + nal->i_payload;
    uint8_t *orig_dst = dst;
    //起始码 ==========================================
    //annexb格式，起始码为0x00000001
    if( h->param.b_annexb )
    {
        if( nal->b_long_startcode )
            *dst++ = 0x00;
        *dst++ = 0x00;
        *dst++ = 0x00;
        *dst++ = 0x01;
    }
    else /* save room for size later */
        dst += 4;//mp4格式

    //NALU Header =======================================
    /* nal header */
    *dst++ = ( 0x00 << 7 ) | ( nal->i_ref_idc << 5 ) | nal->i_type;

    dst = h->bsf.nal_escape( dst, src, end );
    int size = (dst - orig_dst) - 4;

    /* Write the size header for mp4/etc */
    //重新回到起始码的位置，写入mp4格式的起始码（size大小，不含起始码）
    if( !h->param.b_annexb )
    {
        /* Size doesn't include the size of the header we're writing now. */
        orig_dst[0] = size>>24;
        orig_dst[1] = size>>16;
        orig_dst[2] = size>> 8;
        orig_dst[3] = size>> 0;
    }
    //NALU负载大小，包含起始码
    nal->i_payload = size+4;
    nal->p_payload = orig_dst;
    x264_emms();
}
```

从源代码可以看出，x264_nal_encode()给NALU数据添加了起始码以及NALU Header。在这里简单总结一下起始码的添加过程。

H.264码流有两种格式：

（1）annexb模式（传统模式）。这种模式下每个NALU包含起始码0x00000001；而且SPS、PPS存储在ES码流中。常见的H.264裸流就是属于这种格式。

（2）mp4模式。这种模式下每个NALU不包含起始码，原本存储起始码前4个字节存储的是这个NALU的长度（不包含前4字节）；而且SPS、PPS被单独放在容器的其他位置上。这种H.264一般存储在某些容器中，例如MP4中。

从源代码中可以看出，x264_nal_encode()根据H.264码流格式的不同分成两种情况给NALU添加起始码：

（1）annexb模式下，在每个NALU前面添加0x00000001。

（2）mp4模式下，先计算NALU的长度（不包含前4字节），再将长度信息写入NALU前面的4个字节

至此有关编码器主干部分有关x264_encoder_encode()的源代码就分析完了。从下一篇文章开始将会开始分析编码Slice的函数——x264_slice_write()。

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