entity-cpu-global-load计算原理

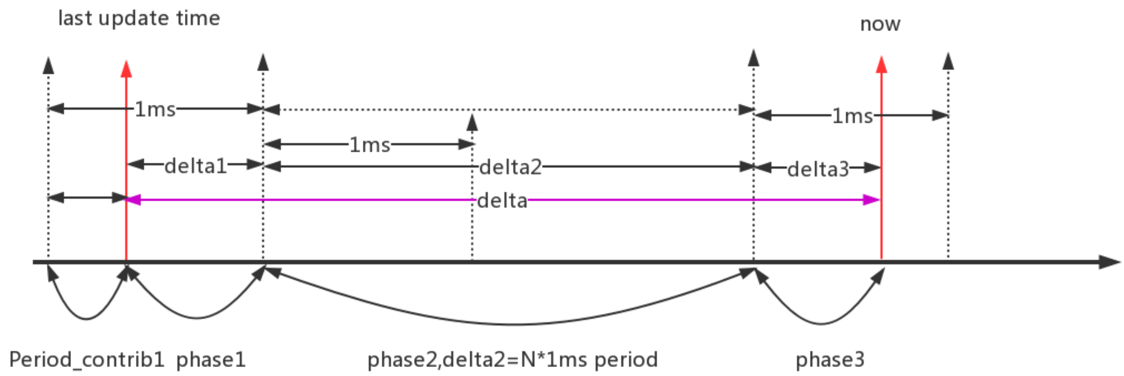
1 PELT(Per Entity Load Tracing)算法 1
1.1 PELT算法概述 2
1.2 PELT算法伪码 2
1.3 decay_load: 3
1.4 __contrib: 4
1.5 详细证明负载衰减累加的原理 6
2 PELT Entity级的负载计算 9
2.1 核心函数1 __update_load_avg()的实现 10
2.2 核心函数2 update_cfs_rq_load_avg()的实现 15
3 CPU级的负载计算update_cpu_load_active(rq) 16
4 系统级的负载计算calc_global_load_tick() 20

Scheduler里面这个负载的概念可能被误解为cpu占用率，但是在调度里面这个有比较大的偏差。scheduler不使用cpu占用率来评估负载，而是使用runnable_time_avg,即平均运行时间来评估负载。sheduler也分了几个层级来计算负载：

- entity级负载计算：update_load_avg()
- cpu级负载计算：update_cpu_load_active()
- 系统级负载计算：calc_global_load_tick()

1 PELT(Per Entity Load Tracing)算法

第一个是调度实体的load,即sched_entity的load,根据PELT算法实现的,算法逻辑如下:



1.1 PELT算法概述

从上面示意图可以看到,task runtime是delta=delta1+delta2+delta3之和

- delta数值依赖真实task的运行时间,是总的运行时间
- last update time是task load是上次更新的最后时间(第一个红色箭头)
- now是task load更新的当前时间(第二个红色箭头)
- 1ms表示1024us的颗粒度,由于kernel对于除法效率较和不能使用小数低,所以1ms直接转化为1024us,好做乘法和位移运算,真的很巧妙

示意图的目的就是追踪三个时间段(phase1/phase2/phase3)的load,来计算now时刻的load,周而复始.

1.2 PELT算法伪码

Phase1阶段怎么计算load

1. 计算delta1的period:
   delta1 = 1024 - Period_contrib1 （< 1024us）
2. load_sum被刻度化通过当前cpu频率和se的权重:
   delta1 = delta1 * scale_freq
   load_sum += weight*delta1
3. load_util被cpu的capacity刻度化
   util_sum += scale_cpu *delta1;

Phase2阶段怎么计算load的:

1. 计算delta2的period
   periods = delta2 / 1024(即存在有多少个1ms)
2. 衰减phase1的load
   load_sum += decay_load(load_sum , periods + 1)
   util_sum += decay_load(util_sum , periods + 1)
3. 衰减阶段phase2的load
   load_sum += __contrib(periods) * scale_freq
   util_sum += __contrib(periods) * scale_freq * scale_cpu

Phase3阶段怎么计算load:

1. 计算剩余周期(<1ms,<1024us)
   period_contrid2 = delta3 % 1024
2. load_sum被当前权重和频率刻度化
   load_sum += weight * scale_freq * period_contrib2
3. util_sum被当前频率和当前cpu capacity刻度化
   util_sum += scale_cpu * scale_freq * period_contrib2

上面是这个算法的精髓以及思路,下面讲解decay_load和__contrib怎么计算的

1.3 decay_load:

对于每一个period(大小为LOAD_AVG_PERIOD=32ms),这个load将衰减0.5,因此根据当前period,load被衰减方式如下:

1. load = (load >> (n/period)) * y^(n%period)
2. 并且y^(n%period) * 2^32 可以看成runnable_avg_yN_inv[n]的数值

在kernel中查表即可:

```
/* Precomputed fixed inverse multiplies for multiplication by y^n */
static const u32 runnable_avg_yN_inv[] = {
    0xffffffff, 0xfa83b2da, 0xf5257d14, 0xefe4b99a, 0xeac0c6e6, 0xe5b906e6,
    0xe0ccdeeb, 0xdbfbb796, 0xd744fcc9, 0xd2a81d91, 0xce248c14, 0xc9b9bd85,
    0xc5672a10, 0xc12c4cc9, 0xbd08a39e, 0xb8fbaf46, 0xb504f333, 0xb123f581,
    0xad583ee9, 0xa9a15ab4, 0xa5fed6a9, 0xa2704302, 0x9ef5325f, 0x9b8d39b9,
    0x9837f050, 0x94f4efa8, 0x91c3d373, 0x8ea4398a, 0x8b95c1e3, 0x88980e80,
    0x85aac367, 0x82cd8698,
};
#define LOAD_AVG_PERIOD 32
#define LOAD_AVG_MAX 47742 /* maximum possible load avg */
#define LOAD_AVG_MAX_N 345 /* number of full periods to produce LOAD_AVG_MAX
*/
```

其实现代码如下:

```
/*
 * Approximate:
 *   val * y^n,    where y^32 ~= 0.5 (~1 scheduling period)
 */
static __always_inline u64 decay_load(u64 val, u64 n)
{
    unsigned int local_n;

    if (!n)
        return val;
    else if (unlikely(n > LOAD_AVG_PERIOD * 63))
        return 0;

    /* after bounds checking we can collapse to 32-bit */
    local_n = n;

    /*
     * As y^PERIOD = 1/2, we can combine
```

```
         *    y^n = 1/2^(n/PERIOD) * y^(n%PERIOD)
         * With a look-up table which covers y^n (n<PERIOD)
         *
         * To achieve constant time decay_load.
         */  /*LOAD_AVG_PERIOD = 32*/
        if (unlikely(local_n >= LOAD_AVG_PERIOD)) {
            val >>= local_n / LOAD_AVG_PERIOD;
            local_n %= LOAD_AVG_PERIOD;
        }
        /*正好符合:load = (load >> (n/period)) * y^(n%period)计算方式*/
        val = mul_u64_u32_shr(val, runnable_avg_yN_inv[local_n], 32);
        return val;
    }
```

1.4 __contrib:

1. if period <= LOAD_AVG_PERIOD(32ms, 32 * 1024us)
   load = 1024 + 1024*y + 1024*y^2 + ……+1024*y^period
2. **if period > LOAD_AVG_MAX_N(345ms)**
   load = LOAD_AVG_MAX (47742)
3. if period∈(32, 345],即每个LOAD_AVG_PERIOD周期衰减累加
   do
      load /=2
      load += 1024 + 1024*y + 1024*y^2 +.....+ 1024*y^LOAD_AVG_PERIOD
      n -= period
   while(n > LOAD_AVG_PERIOD)
4. 1024 + 1024*y + 1024*y^2 +.....+ 1024*y^32=runnable_avg_yN_sum[32]
   decay_load()只是计算y^n，而__contrib是计算一个对比队列的和：y + y^2 + y^3 … + y^n.计算方式如下:
   runnable_avg_yN_sum[]数组是使用查表法来计算n=32位内的等比队列求和:
   runnable_avg_yN_sum[1] = y^1 * 1024 = 0.978520621 * 1024 = 1002
   runnable_avg_yN_sum[2] = (y^1 + y^2) * 1024 = 1982
   …
   runnable_avg_yN_sum[32] = (y^1 + y^2 .. + y^32) * 1024 = 23371

实现代码和查表数据如下:

```
static u32 __compute_runnable_contrib(u64 n)
{
    u32 contrib = 0;

    if (likely(n <= LOAD_AVG_PERIOD))
        return runnable_avg_yN_sum[n];
    else if (unlikely(n >= LOAD_AVG_MAX_N))
        return LOAD_AVG_MAX;

    /* Compute \Sum k^n combining precomputed values for k^i, \Sum k^j */
    do {
        contrib /= 2; /* y^LOAD_AVG_PERIOD = 1/2 */
        contrib += runnable_avg_yN_sum[LOAD_AVG_PERIOD];

```

```
        n -= LOAD_AVG_PERIOD;
    } while (n > LOAD_AVG_PERIOD);

    contrib = decay_load(contrib, n);
    return contrib + runnable_avg_yN_sum[n];
}
/*
 * Precomputed \Sum y^k { 1<=k<=n }.  These are floor(true_value) to prevent
 * over-estimates when re-combining.
 */
static const u32 runnable_avg_yN_sum[] = {
        0, 1002, 1982, 2941, 3880, 4798, 5697, 6576, 7437, 8279, 9103,
     9909,10698,11470,12226,12966,13690,14398,15091,15769,16433,17082,
    17718,18340,18949,19545,20128,20698,21256,21802,22336,22859,23371,
};
```

针对__contrib第二点当period>345的时候,load变成一个常数怎么理解的?

即**load = LOAD_AVG_MAX (47742),我们简单来证明以下:**

设一个等比数列的首项是a1,公比是y，数列前n项和是Sn，当公比不为1时

$$S_n=a_1+a_1y+a_1y^2+...+a_1y^{(n-1)}$$

将这个式子两边同时乘以公比y，得

$$yS_n=a_1y+a_1y^2+...+a_1y^{(n-1)}+a_1y^n$$

两式相减，得

$$(1-y)S_n=a_1-a_1y^n$$

所以，当公比不为1时，等比数列的求和公式:

$$S_n=a_1(1-y^n)/(1-y)$$

对于一个无穷递降数列，数列的公比小于1,当上式得n趋向于正无穷大时，分子括号中的值趋近于1，取极限即得无穷递减数列求和公式:

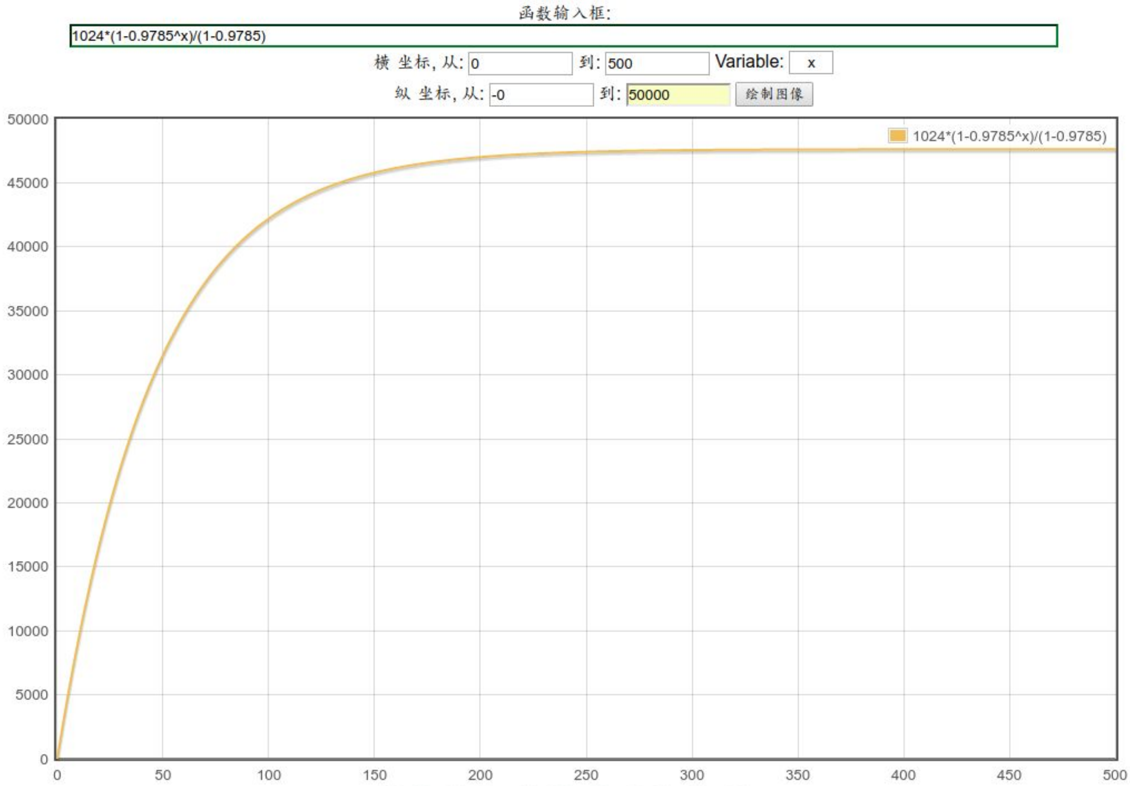
$$S=a_1/(1-y)$$

由于要使$y^{32} = 0.5$, 那么经过计算之后,$y \approx 0.9785$ ($0.9785^{32} \approx 0.498823$)

所以对于period > **LOAD_AVG_MAX_N(345)**,等比数列求和数值如下:

$$s_n=a_1(1-y^n)/(1-y)=1024*(1-0.9785^n)/(1-0.9785)\approx 1002*(1-0.9785^n)$$

画出曲线图如下:



从当n趋于一个数值，当n增大，等比数列之后增加几乎可以忽略，并且无穷大∞,则等比数列之和为a1/(1-y)=1024/(1-0.9785)≈47627.9069988967,与47742数值差不多.

1.5 详细证明负载衰减累加的原理

那么上面的两个表格runnable_avg_yN_inv和runnable_avg_yN_sum是怎么计算的,下面是一个通过C语言计算的小程序:

```
#include <stdio.h>
#include <math.h>
#if 1
#define N 32
#define WMULT_SHIFT 32

const long WMULT_CONST = ((1UL << N) - 1);
double y;

long runnable_avg_yN_inv[N];
void calc_mult_inv()
{
    int i;
    double yn = 0;

    printf("inverses\n");
    for (i = 0; i < N; i++) {
        yn = (double)WMULT_CONST * pow(y, i);
        runnable_avg_yN_inv[i] = yn;
        printf("%2d: 0x%8lx\n", i, runnable_avg_yN_inv[i]);
    }
```

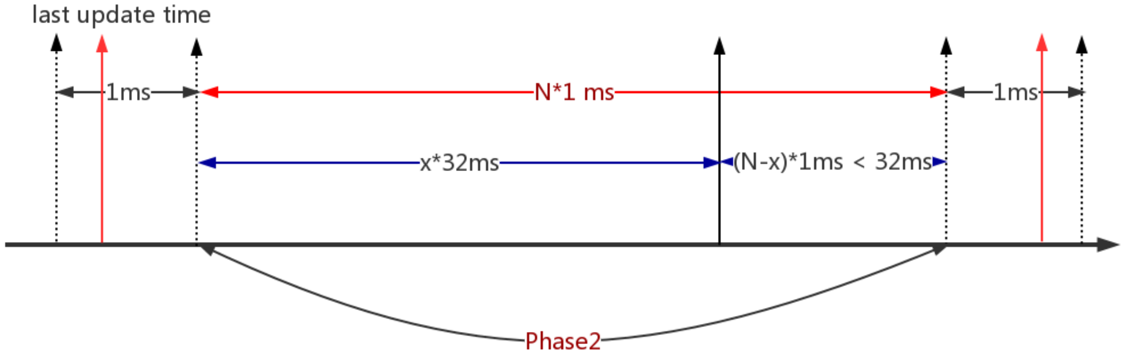
```
    printf("\n");
}

long mult_inv(long c, int n)
{
    return (c * runnable_avg_yN_inv[n]) >>  WMULT_SHIFT;
}

void calc_yn_sum(int n)
{
    int i;
    double sum = 0, sum_fl = 0, diff = 0;

    /*
     * We take the floored sum to ensure the sum of partial sums is never
     * larger than the actual sum.
     */
    printf("sum y^n\n");
    printf("   %8s  %8s %8s\n", "exact", "floor", "error");
    for (i = 1; i <= n; i++) {
        sum = (y * sum + y * 1024);
        sum_fl = floor(y * sum_fl+ y * 1024);
        printf("%2d: %8.0f  %8.0f %8.0f\n", i, sum, sum_fl,
            sum_fl - sum);
    }
    printf("\n");
}

void calc_conv(long n)
{
    long old_n;
    int i = -1;

    printf("convergence (LOAD_AVG_MAX, LOAD_AVG_MAX_N)\n");
    do {
        old_n = n;
        n = mult_inv(n, 1) + 1024;
        i++;
    } while (n != old_n);
    printf("%d> %ld\n", i - 1, n);
    printf("\n");
}

#endif
int  main(void)
{
#if 1
    /* y^32 = 0.5,so y=pow(0.5,32.0)*/
    y = pow(0.5, 1/(double)N);
    calc_mult_inv();
    calc_conv(1024);
    calc_yn_sum(N);
#endif

```

```
        return 0;
}
```
runnable_avg_yN_inv[i]的数值如下:
0: 0xffffffff
1: 0xfa83b2da
2: 0xf5257d14
3: 0xefe4b99a
4: 0xeac0c6e6
5: 0xe5b906e6
6: 0xe0ccdeeb
7: 0xdbfbb796
8: 0xd744fcc9
9: 0xd2a81d91
10: 0xce248c14
11: 0xc9b9bd85
12: 0xc5672a10
13: 0xc12c4cc9
14: 0xbd08a39e
15: 0xb8fbaf46
16: 0xb504f333
17: 0xb123f581
18: 0xad583ee9
19: 0xa9a15ab4
20: 0xa5fed6a9
21: 0xa2704302
22: 0x9ef5325f
23: 0x9b8d39b9
24: 0x9837f050
25: 0x94f4efa8
26: 0x91c3d373
27: 0x8ea4398a
28: 0x8b95c1e3
29: 0x88980e80
30: 0x85aac367
31: 0x82cd8698
与table是吻合的.
也就是说两个table的通项公式如下(我们知道y^32约等于0.5推导出y=0.9785):

runnable_avg_yN_inv[n]=(2^32-1) * (0.9785^n);

runnable_avg_yN_sum[n]=1024*(y + y^2+..+y^n);

所以在函数decay_load的时候,需要>> 32,这是单个时间点的衰减数值
下面画一张图来详细说明上面的逻辑关系:



decay_load是计算Phase2的一个load的衰减,比如在Phase2起始阶段load为load_x,经过两个阶段的衰减:

- x*32ms=(N/32) * 32之后变为:load_x >> (N/32),即每隔32ms,load_x衰减一半,符合y^32=0.5.
- 那么剩下的(N-x)ms,继续衰减,使用公式计算即:(load_x >> (N/32)) * y^(N-x).这样就明白了.单个load的衰减计算方式.

对于累加load的计算方式也使用这张图来说明:
__compute_runnable_contrib(N)怎么来计算累加的负载:

- x*32ms=(N/32) * 32,可以根据查表计是32ms倍数的周期内,累加的负载可以通过查表获取,并且累加的负载在每个32ms周期都会衰减一半,23371=runnable_avg_yN_sum[31].即计算公式如下:

$$contrib = \frac{\frac{\frac{contrib+23371}{2}+23371}{2}+23371}{2}+\ldots.$$

或者:
contrib = 1024(y+y^2+..+y^32+...+y^64...) = 1024(y+..+y^32)+y^32*1024(y+..+y32)...
由于y^32=0.5.所以可以对上

- 对前x*32ms已经累加了,现在需要对这部分在(N-x)ms进行衰减操作,即contrib=decay_load(contrib,N-x)
- 最后计算contrib+runnable_avg_yN_sum[N-x]就是最后累加的结果了.

最后decay_load的数值+contrib的数值就是经过衰减之后, 在第二虚线处的总负载。

2 PELT Entity级的负载计算

- Entity级的负载计算也称作PELT(Per-Entity Load Tracking)。
- 注意负载计算时使用的时间都是实际运行时间而不是虚拟运行时间vruntime。

过程如下:

```
scheduler_tick() -> task_tick_fair() -> entity_tick() -> update_load_avg()
/* Update task and its cfs_rq load average */
static inline void update_load_avg(struct sched_entity *se, int flags)
{
    struct cfs_rq *cfs_rq = cfs_rq_of(se);
```

```
    u64 now = cfs_rq_clock_task(cfs_rq);
    int cpu = cpu_of(rq_of(cfs_rq));
    int decayed;
    void *ptr = NULL;

    /*
     * Track task load average for carrying it to new CPU after migrated,
and
     * track group sched_entity load average for task_h_load calc in
migration
     *//*cfs load tracing时间已经update,也就是已经初始化过了
     SKIP_AGE_LOAD是忽略load tracing的flag*/
    if (se->avg.last_update_time && !(flags & SKIP_AGE_LOAD)) {
        /*核心函数,即PELT的实现,注意se->on_rq的数值,如果一直在运行的进程,则
    se->on_rq,load=老负载衰减+新负载,如果是休眠唤醒进程se->on_rq=0,则他们在
     休眠期间的load不会累加,只有老负载被衰减,睡眠时间不会统计在内,直到task在rq里面*/
        __update_load_avg(now, cpu, &se->avg,
              se->on_rq * scale_load_down(se->load.weight),
              cfs_rq->curr == se, NULL);
    }

    decayed  = update_cfs_rq_load_avg(now, cfs_rq, true);
    decayed |= propagate_entity_load_avg(se);

    if (decayed && (flags & UPDATE_TG))
        update_tg_load_avg(cfs_rq, 0);

    if (entity_is_task(se)) {
#ifdef CONFIG_SCHED_WALT
        ptr = (void *)&(task_of(se)->ravg);
#endif
        trace_sched_load_avg_task(task_of(se), &se->avg, ptr);
    }
}
```

2.1 核心函数1 __update_load_avg()的实现

我们先明白下面几个参数的含义:

1. load_sum
2. util_sum
3. load_avg
4. util_avg

上面几个涉及到cfs_rq结构体的成员变量:

```
struct cfs_rq {
..............
    /*
     * CFS load tracking
     */
    struct sched_avg avg;
    u64 runnable_load_sum;
    unsigned long runnable_load_avg;
..............
}
```

```
/*
 * The load_avg/util_avg accumulates an infinite geometric series.
 * 1) load_avg factors frequency scaling into the amount of time that a
 * sched_entity is runnable on a rq into its weight. For cfs_rq, it is the
 * aggregated such weights of all runnable and blocked sched_entities.
 * 2) util_avg factors frequency and cpu scaling into the amount of time
 * that a sched_entity is running on a CPU, in the range
[0..SCHED_LOAD_SCALE].
 * For cfs_rq, it is the aggregated such times of all runnable and
 * blocked sched_entities.
 * The 64 bit load_sum can:
 * 1) for cfs_rq, afford 4353082796 (=2^64/47742/88761) entities with
 * the highest weight (=88761) always runnable, we should not overflow
 * 2) for entity, support any load.weight always runnable
 */
struct sched_avg {
    u64 last_update_time, load_sum;
    u32 util_sum, period_contrib;
    unsigned long load_avg, util_avg;
};
```

而且如果知道了load_sum,util_sum,runnable_load_sum,这几个数值除以LOAD_AVG_MAX(**47742**)则就可以直接计算load_avg,util_avg,runnable_load_avg,即:
util_avg = util_sum / **LOAD_AVG_MAX(47742).**

5. scale_freq:当前频率与最大频率相除 ×1024
6. scale_cpu:当前cpu capacity

关键函数的代码如下:

```
/*
 * We can represent the historical contribution to runnable average as the
 * coefficients of a geometric series.  To do this we sub-divide our
runnable
 * history into segments of approximately 1ms (1024us); label the segment
that
 * occurred N-ms ago p_N, with p_0 corresponding to the current period, e.g.
 *
 * [<- 1024us ->|<- 1024us ->|<- 1024us ->| ...
 *      p0            p1           p2
 *     (now)       (~1ms ago)  (~2ms ago)
 *
 * Let u_i denote the fraction of p_i that the entity was runnable.
 *
 * We then designate the fractions u_i as our co-efficients, yielding the
 * following representation of historical load:
 *   u_0 + u_1*y + u_2*y^2 + u_3*y^3 + ...
 *
 * We choose y based on the with of a reasonably scheduling period, fixing:
 *   y^32 = 0.5
 *
 * This means that the contribution to load ~32ms ago (u_32) will be
weighted
 * approximately half as much as the contribution to load within the last ms
 * (u_0).
 *
 * When a period "rolls over" and we have new u_0`, multiplying the previous
```

```
 * sum again by y is sufficient to update:
 *   load_avg = u_0` + y*(u_0 + u_1*y + u_2*y^2 + ... )
 *            = u_0 + u_1*y + u_2*y^2 + ... [re-labeling u_i --> u_{i+1}]
 */
static __always_inline int
__update_load_avg(u64 now, int cpu, struct sched_avg *sa,
          unsigned long weight, int running, struct cfs_rq *cfs_rq)
{
    u64 delta, scaled_delta, periods;
    u32 contrib;
    unsigned int delta_w, scaled_delta_w, decayed = 0;
    unsigned long scale_freq, scale_cpu;

#ifdef CONFIG_64BIT_ONLY_CPU
    struct sched_entity *se;
    unsigned long load_avg_before = sa->load_avg;
#endif
    /*就是示意图中的delta1+delta2+delta3*/
    delta = now - sa->last_update_time;
    /*
     * This should only happen when time goes backwards, which it
     * unfortunately does during sched clock init when we swap over to TSC.
     */
    if ((s64)delta < 0) {
        sa->last_update_time = now;
        return 0;
    }

    /*
     * Use 1024ns as the unit of measurement since it's a reasonable
     * approximation of 1us and fast to compute.
     */
    delta >>= 10;
    if (!delta)
        return 0;
    sa->last_update_time = now;
    /*scale_freq = (curr_freq << 10)/policy->max*/
    scale_freq = arch_scale_freq_capacity(NULL, cpu);
    /*scale_cpu = capacity[cpu],dts获取的,不同cluster capacity不同*/
    scale_cpu = arch_scale_cpu_capacity(NULL, cpu);
    trace_sched_contrib_scale_f(cpu, scale_freq, scale_cpu);

    /* delta_w is the amount already accumulated against our next period */
    delta_w = sa->period_contrib;
    /*表示delta1+delta2大于一个最小刻度1024,如果小于,则就只剩下delta3计算,delta1,
    delta2不存在*/
    if (delta + delta_w >= 1024) {
        decayed = 1;

        /* how much left for next period will start over, we don't know yet
*/
        sa->period_contrib = 0;

        /*
```

```
             * Now that we know we're crossing a period boundary, figure
             * out how much from delta we need to complete the current
             * period and accrue it.
             */
            /*开始Phase1阶段的load_sum 和util_sum的计算*/
            delta_w = 1024 - delta_w;
            scaled_delta_w = cap_scale(delta_w, scale_freq);
            if (weight) {
                sa->load_sum += weight * scaled_delta_w;
                if (cfs_rq) {
                    cfs_rq->runnable_load_sum +=
                            weight * scaled_delta_w;
                }
            }
            if (running)
                sa->util_sum += scaled_delta_w * scale_cpu;
            /*结束Phase1阶段的load_sum 和util_sum的计算*/
            delta -= delta_w;

            /* Figure out how many additional periods this update spans */
            /*开始Phase2阶段的load_sum 和util_sum的计算,计算阶段Phase2存在多少个1024
             的倍数和余数*/
            periods = delta / 1024;
            delta %= 1024;
            /*对阶段Phase1的load_sum进行衰减*/
            sa->load_sum = decay_load(sa->load_sum, periods + 1);
            if (cfs_rq) {
                /*对阶段Phase1的runnable_load_sum进行衰减*/
                cfs_rq->runnable_load_sum =
                    decay_load(cfs_rq->runnable_load_sum, periods + 1);
            }
            /*对Phase1阶段util_sum进行衰减*/
            sa->util_sum = decay_load((u64)(sa->util_sum), periods + 1);
          /*至此,上面已经得到了阶段Phase2衰减前的load_sum,util_sum,
            runnable_load_sum的数值*/
            /* Efficiently calculate \sum (1..n_period) 1024*y^i */

            /*对Phase2的load/util数据进行衰减*/
            contrib = __compute_runnable_contrib(periods);
            contrib = cap_scale(contrib, scale_freq);
            if (weight) {
                sa->load_sum += weight * contrib;
                if (cfs_rq)
                    cfs_rq->runnable_load_sum += weight * contrib;
            }
            if (running)
                sa->util_sum += contrib * scale_cpu;
        }
         /*结束Phase2阶段的load_sum 和util_sum的计算*/
        /* Remainder of delta accrued against u_0` */
        /*开始阶段Phase3的的load/util的计算*/
        scaled_delta = cap_scale(delta, scale_freq);
        if (weight) {
            sa->load_sum += weight * scaled_delta;
```

```
            if (cfs_rq)
                cfs_rq->runnable_load_sum += weight * scaled_delta;
        }
        if (running)
            sa->util_sum += scaled_delta * scale_cpu;
      /*结束阶段Phase3的的load/util的计算*/
        /*sa->period_contrib ∈[0,1024)*/
        sa->period_contrib += delta;
      /*如果衰减了,则计算load的avg的数值,否则由于颗粒度太小,没有计算的必要*/
        if (decayed) {
            sa->load_avg = div_u64(sa->load_sum, LOAD_AVG_MAX);
            if (cfs_rq) {
                cfs_rq->runnable_load_avg =
                    div_u64(cfs_rq->runnable_load_sum, LOAD_AVG_MAX);
            }
            sa->util_avg = sa->util_sum / LOAD_AVG_MAX;
        }

    #ifdef CONFIG_64BIT_ONLY_CPU
        if (!cfs_rq) {
            if (is_sched_avg_32bit(sa)) {
                se = container_of(sa, struct sched_entity, avg);
                cfs_rq_of(se)->runnable_load_avg_32bit +=
                    sa->load_avg - load_avg_before;
            }
        }
    #endif

        return decayed;
    }
    /*
     * Approximate:
     *   val * y^n,    where y^32 ~= 0.5 (~1 scheduling period)
     */
    static __always_inline u64 decay_load(u64 val, u64 n)
    {
        unsigned int local_n;

        if (!n)
            return val;
        else if (unlikely(n > LOAD_AVG_PERIOD * 63))
            return 0;

        /* after bounds checking we can collapse to 32-bit */
        local_n = n;
        /*计算公式为:load = (load >> (n/period)) * y^(n%period),如果n是32的整数倍
        ，因为2^32 = 1/2，相当于右移一位计算n有多少个32，每个32右移一位*/
        /*
         * As y^PERIOD = 1/2, we can combine
         *    y^n = 1/2^(n/PERIOD) * y^(n%PERIOD)
         * With a look-up table which covers y^n (n<PERIOD)
         *
         * To achieve constant time decay_load.
         */
```

```
    if (unlikely(local_n >= LOAD_AVG_PERIOD)) {
        val >>= local_n / LOAD_AVG_PERIOD;
        local_n %= LOAD_AVG_PERIOD;
    }
    /*将val*y^32,转化为val*runnable_avg_yN_inv[n%LOAD_AVG_PERIOD]>>32*/
    val = mul_u64_u32_shr(val, runnable_avg_yN_inv[local_n], 32);
    return val;
}
/*
 * For updates fully spanning n periods, the contribution to runnable
 * average will be: \Sum 1024*y^n
 *
 * We can compute this reasonably efficiently by combining:
 *   y^PERIOD = 1/2 with precomputed \Sum 1024*y^n {for  n <PERIOD}
 */
static u32 __compute_runnable_contrib(u64 n)
{
    u32 contrib = 0;

    if (likely(n <= LOAD_AVG_PERIOD))
        return runnable_avg_yN_sum[n];
    else if (unlikely(n >= LOAD_AVG_MAX_N))
        return LOAD_AVG_MAX;
    /*如果n>32, 计算32的整数部分*/
    /* Compute \Sum k^n combining precomputed values for k^i, \Sum k^j */
    do {
        /*每整数32的衰减就是0.5*/
        contrib /= 2; /* y^LOAD_AVG_PERIOD = 1/2 */
        contrib += runnable_avg_yN_sum[LOAD_AVG_PERIOD];

        n -= LOAD_AVG_PERIOD;
    } while (n > LOAD_AVG_PERIOD);

    /*将整数部分对余数n进行衰减*/
    contrib = decay_load(contrib, n);
    /*剩余余数n, 使用查表法计算*/
    return contrib + runnable_avg_yN_sum[n];
}

```

2.2 核心函数2 update_cfs_rq_load_avg()的实现

```
/**
 * update_cfs_rq_load_avg - update the cfs_rq's load/util averages
 * @now: current time, as per cfs_rq_clock_task()
 * @cfs_rq: cfs_rq to update
 * @update_freq: should we call cfs_rq_util_change() or will the call do so
 *
 * The cfs_rq avg is the direct sum of all its entities (blocked and
runnable)
 * avg. The immediate corollary is that all (fair) tasks must be attached,
see
 * post_init_entity_util_avg().
 *
```

```
 * cfs_rq->avg is used for task_h_load() and update_cfs_share() for example.
 *
 * Returns true if the load decayed or we removed load.
 *
 * Since both these conditions indicate a changed cfs_rq->avg.load we should
 * call update_tg_load_avg() when this function returns true.
 */
static inline int
update_cfs_rq_load_avg(u64 now, struct cfs_rq *cfs_rq, bool update_freq)
{
    struct sched_avg *sa = &cfs_rq->avg;
    int decayed, removed = 0, removed_util = 0;
    /*是否设置了remove_load_avg和remove_util_avg,如果设置了就修正之前计算的
    load/util数值*/
    if (atomic_long_read(&cfs_rq->removed_load_avg)) {
        s64 r = atomic_long_xchg(&cfs_rq->removed_load_avg, 0);
        sub_positive(&sa->load_avg, r);
        sub_positive(&sa->load_sum, r * LOAD_AVG_MAX);
        removed = 1;
        set_tg_cfs_propagate(cfs_rq);
    }

    if (atomic_long_read(&cfs_rq->removed_util_avg)) {
        long r = atomic_long_xchg(&cfs_rq->removed_util_avg, 0);
        sub_positive(&sa->util_avg, r);
        sub_positive(&sa->util_sum, r * LOAD_AVG_MAX);
        removed_util = 1;
        set_tg_cfs_propagate(cfs_rq);
    }
   /*对校准后的load进行重新计算*/
    decayed = __update_load_avg(now, cpu_of(rq_of(cfs_rq)), sa,
        scale_load_down(cfs_rq->load.weight), cfs_rq->curr != NULL, cfs_rq);

#ifndef CONFIG_64BIT
    smp_wmb();
    cfs_rq->load_last_update_time_copy = sa->last_update_time;
#endif

    /* Trace CPU load, unless cfs_rq belongs to a non-root task_group */
    if (cfs_rq == &rq_of(cfs_rq)->cfs)
        trace_sched_load_avg_cpu(cpu_of(rq_of(cfs_rq)), cfs_rq);
    /*如果为true,则调用schedutil governor进行频率的调整!!!*/
    if (update_freq)
        cfs_rq_util_change(cfs_rq);

    return decayed || removed;
}
```
update_load_avg剩下的函数执行如下:

- propagate_entity_load_avg,更新调度实体本身自己的load/util信息.如果是一个进程则不需要propagate处理.
- 根据decayed的数值和需要更新进程组信息,则调用update_tg_load_avg,更新task_group信息

3 CPU级的负载计算update_cpu_load_active(rq)

__update_load_avg()是计算se/cfs_rq级别的负载，在cpu级别linux使用update_cpu_load_active(rq)来计算整个cpu->rq负载的变化趋势。计算也是周期性的，周期为TICK(时间不固定,由于是tickless系统)。

```
scheduler_tick()----->
/*
 * Called from scheduler_tick()
 */
void update_cpu_load_active(struct rq *this_rq)
{   /*获取cfs_rq的runnable_load_avg的数值*/
    unsigned long load = weighted_cpuload(cpu_of(this_rq));
    /*
     * See the mess around update_idle_cpu_load() / update_cpu_load_nohz().
     */   /*设置更新rq load的时间戳*/
    this_rq->last_load_update_tick = jiffies;
   /核心函数*/
    __update_cpu_load(this_rq, load, 1);
}
/* Used instead of source_load when we know the type == 0 */
static unsigned long weighted_cpuload(const int cpu)
{
    return cfs_rq_runnable_load_avg(&cpu_rq(cpu)->cfs);
}

static inline unsigned long cfs_rq_runnable_load_avg(struct cfs_rq *cfs_rq)
{
    /*这个数值在setity级别的计算过程中已经update了*/
    return cfs_rq->runnable_load_avg;
}

/*
 * Update rq->cpu_load[] statistics. This function is usually called every
 * scheduler tick (TICK_NSEC). With tickless idle this will not be called
 * every tick. We fix it up based on jiffies.
 */
static void __update_cpu_load(struct rq *this_rq, unsigned long this_load,
                  unsigned long pending_updates)
{
    int i, scale;
    /*统计数据使用*/
    this_rq->nr_load_updates++;

    /* Update our load: */
    /*将当前最新的load,更新在cpu_load[0]中*/
    this_rq->cpu_load[0] = this_load; /* Fasttrack for idx 0 */
    for (i = 1, scale = 2; i < CPU_LOAD_IDX_MAX; i++, scale += scale) {
        unsigned long old_load, new_load;

        /* scale is effectively 1 << i now, and >> i divides by scale */

```

```
            old_load = this_rq->cpu_load[i];
            /*对old_load进行衰减.果因为进入noHZ模式, 有pending_updates个tick没有
             更新, 先老化原有负载*/
            old_load = decay_load_missed(old_load, pending_updates - 1, i);
            new_load = this_load;
            /*
             * Round up the averaging division if load is increasing. This
             * prevents us from getting stuck on 9 if the load is 10, for
             * example.
             */
            if (new_load > old_load)
                new_load += scale - 1;
            /*cpu_load的计算公式 */
            this_rq->cpu_load[i] = (old_load * (scale - 1) + new_load) >> i;
        }
        /*更新rq的age_stamp时间戳,即rq从cpu启动到现在存在的时间(包括idle和running时间)
        ,同时更新rq里面rt_avg负载,即每个周期(500ms)衰减一半*/
        sched_avg_update(this_rq);
    }
    void sched_avg_update(struct rq *rq)
    {
        s64 period = sched_avg_period();

        while ((s64)(rq_clock(rq) - rq->age_stamp) > period) {
            /*
             * Inline assembly required to prevent the compiler
             * optimising this loop into a divmod call.
             * See __iter_div_u64_rem() for another example of this.
             */
            asm("" : "+rm" (rq->age_stamp));
            rq->age_stamp += period;
            rq->rt_avg /= 2;
        }
    }

```

代码注释中详细解释了cpu_load的计算方法：

- 每个tick计算不同idx时间等级的load，计算公式：load = (2^idx - 1) / 2^idx * load + 1 / 2^idx * cur_load
- 如果cpu因为noHZ错过了(n-1)个tick的更新，那么计算load要分两步：
    1. 首先老化(decay)原有的load：load = ((2^idx - 1) / 2^idx)^(n-1) * load
    2. 再按照一般公式计算load：load = load = (2^idx - 1) / 2^idx) * load + 1 / 2^idx * cur_load
- 为了decay的加速计算，设计了decay_load_missed()查表法计算：

```
/*
 * The exact cpuload at various idx values, calculated at every tick would be
 * load = (2^idx - 1) / 2^idx * load + 1 / 2^idx * cur_load
 *
 * If a cpu misses updates for n-1 ticks (as it was idle) and update gets called
 * on nth tick when cpu may be busy, then we have:
 * load = ((2^idx - 1) / 2^idx)^(n-1) * load
 * load = (2^idx - 1) / 2^idx) * load + 1 / 2^idx * cur_load
 *
 * decay_load_missed() below does efficient calculation of
```

```
 * load = ((2^idx - 1) / 2^idx)^(n-1) * load
 * avoiding 0..n-1 loop doing load = ((2^idx - 1) / 2^idx) * load
 *
 * The calculation is approximated on a 128 point scale.
 * degrade_zero_ticks is the number of ticks after which load at any
 * particular idx is approximated to be zero.
 * degrade_factor is a precomputed table, a row for each load idx.
 * Each column corresponds to degradation factor for a power of two ticks,
 * based on 128 point scale.
 * Example:
 * row 2, col 3 (=12) says that the degradation at load idx 2 after
 * 8 ticks is 12/128 (which is an approximation of exact factor 3^8/4^8).
 *
 * With this power of 2 load factors, we can degrade the load n times
 * by looking at 1 bits in n and doing as many mult/shift instead of
 * n mult/shifts needed by the exact degradation.
 */
#define DEGRADE_SHIFT       7
static const unsigned char
        degrade_zero_ticks[CPU_LOAD_IDX_MAX] = {0, 8, 32, 64, 128};
static const unsigned char
        degrade_factor[CPU_LOAD_IDX_MAX][DEGRADE_SHIFT + 1] = {
                    {0, 0, 0, 0, 0, 0, 0, 0},
                    {64, 32, 8, 0, 0, 0, 0, 0},
                    {96, 72, 40, 12, 1, 0, 0},
                    {112, 98, 75, 43, 15, 1, 0},
                    {120, 112, 98, 76, 45, 16, 2} };

/*
 * Update cpu_load for any missed ticks, due to tickless idle. The backlog
 * would be when CPU is idle and so we just decay the old load without
 * adding any new load.
 */
static unsigned long
decay_load_missed(unsigned long load, unsigned long missed_updates, int idx)
{
    int j = 0;

```

```
    if (!missed_updates)
        return load;

    if (missed_updates >= degrade_zero_ticks[idx])
        return 0;

    if (idx == 1)
        return load >> missed_updates;

    while (missed_updates) {
        if (missed_updates % 2)
            load = (load * degrade_factor[idx][j]) >> DEGRADE_SHIFT;

            missed_updates >>= 1;
            j++;
    }
    return load;
}
```

- cpu_load[]含5条均线，反应不同时间窗口长度下的负载情况；主要供load_balance()在不同场景判断是否负载平衡的比较基准，常用为cpu_load[0]和cpu_load[1];
- cpu_load[index]对应的时间长度为{0, 8, 32, 64, 128}，单位为tick;
- 移动均线的目的在于平滑样本的抖动，确定趋势的变化方向;

4 系统级的负载计算calc_global_load_tick()

系统级的平均负载(load average)可以通过以下命令(uptime、top、cat /proc/loadavg)查看：

```
mate20:/ # cat proc/loadavg && uptime
1.38 1.49 1.58 1/1085 20184
 16:10:43 up 1 day,  2:29,  0 users,  load average: 1.38, 1.49, 1.58
```

“load average:”后面的3个数字分别表示1分钟、5分钟、15分钟的load average。可以从几方面去解析load average：

- If the averages are 0.0, then your system is idle.
- If the 1 minute average is higher than the 5 or 15 minute averages, then load is increasing.
- If the 1 minute average is lower than the 5 or 15 minute averages, then load is decreasing.
- If they are higher than your CPU count, then you might have a performance problem (it depends).

最早的系统级平均负载(load average)只会统计runnable状态。但是linux后面觉得这种统计方式代表不了系统的真实负载；举一个例子：系统换一个低速硬盘后，他的 runnable负载还会小于高速硬盘时的值；linux认为睡眠状态(TASK_INTERRUPTIBLE/TASK_UNINTERRUPTIBLE)也是系统的一种负载，系统得不到服

务是因为io/外设的负载过重； 系统级负载统计函数calc_global_load_tick()中会把(this_rq->nr_running+this_rq->nr_uninterruptible)都计入负载.

下面来看看具体的代码计算:
每个cpu每隔5s更新本cpu rq的(nr_running+nr_uninterruptible)任务数量到系统全局变量calc_load_tasks，calc_load_tasks是整系统多个cpu(nr_running+nr_uninterruptible)任 务数量的总和，多cpu在访问calc_load_tasks变量时使用原子操作来互斥。

```
/*
 * Called from scheduler_tick() to periodically update this CPU's
 * active count.
 */
void calc_global_load_tick(struct rq *this_rq)
{
    long delta;
    /*判断5s更新周期是否到达*/
    if (time_before(jiffies, this_rq->calc_load_update))
        return;
    /*计算本cpu的负载变化到全局变量calc_load_tasks中*/
    delta  = calc_load_fold_active(this_rq);
    if (delta)
        atomic_long_add(delta, &calc_load_tasks);
    /*更新calc_load_update时间.LOAD_FREQ:(5*HZ+1),5s*/
    this_rq->calc_load_update += LOAD_FREQ;
}
```

多个cpu更新calc_load_tasks，但是计算load只由一个cpu来完成，这个cpu就是tick_do_timer_cpu。在 linux time一文中，我们看到这个cpu就是专门来更新时间戳timer的(update_wall_time())。实际上它在更新时间戳的同时也会调用 do_timer() -> calc_global_load()来计算系统负载。
核心算法calc_load()的思想也是：旧的load*老化系数 + 新load*系数
假设单位1为FIXED_1=2^11=2028，EXP_1=1884、EXP_5=2014、EXP_15=2037，load的计算：
load = old_load*(EXP_?/FIXED_1) + new_load*(FIXED_1-EXP_?)/FIXED_1

```
do_timer() -> calc_global_load()
↓
void calc_global_load(unsigned long ticks)
{
    long active, delta;

    /* (1) 计算的间隔时间为5s + 10tick,
        加10tick的目的就是让所有cpu都更新完calc_load_tasks,
        tick_do_timer_cpu再来计算
     */
    if (time_before(jiffies, calc_load_update + 10))
        return;

    /*
     * Fold the 'old' idle-delta to include all NO_HZ cpus.
     */
    delta = calc_load_fold_idle();
```

```
    if (delta)
        atomic_long_add(delta, &calc_load_tasks);

    /* (2) 读取全局统计变量 */
    active = atomic_long_read(&calc_load_tasks);
    active = active > 0 ? active * FIXED_1 : 0;

    /* (3) 计算1分钟、5分钟、15分钟的负载 */
    avenrun[0] = calc_load(avenrun[0], EXP_1, active);
    avenrun[1] = calc_load(avenrun[1], EXP_5, active);
    avenrun[2] = calc_load(avenrun[2], EXP_15, active);

    calc_load_update += LOAD_FREQ;

    /*
     * In case we idled for multiple LOAD_FREQ intervals,
       catch up in bulk. */
    calc_global_nohz();
}

|→

/*
 * a1 = a0 * e + a * (1 - e)
 */
static unsigned long
calc_load(unsigned long load, unsigned long exp, unsigned
long active)
{
    unsigned long newload;

    newload = load * exp + active * (FIXED_1 - exp);
    if (active >= load)
        newload += FIXED_1-1;

    return newload / FIXED_1;
}

#define FSHIFT      11      /* nr of bits of precision */
#define FIXED_1     (1<<FSHIFT) /* 1.0 as fixed-point */
#define LOAD_FREQ   (5*HZ+1)    /* 5 sec intervals */
#define EXP_1       1884        /* 1/exp(5sec/1min) as
fixed-point */
#define EXP_5       2014        /* 1/exp(5sec/5min) */
#define EXP_15      2037        /* 1/exp(5sec/15min) */
```

对于cat /proc/loadavg的数值计算源码如下:

```
#define LOAD_INT(x) ((x) >> FSHIFT)
#define LOAD_FRAC(x) LOAD_INT(((x) & (FIXED_1-1)) * 100)

static int loadavg_proc_show(struct seq_file *m, void *v)
```

```
{
    unsigned long avnrun[3];

    get_avenrun(avnrun, FIXED_1/200, 0);
    /*其实还是直接获取系统全局变量,avnrun的数值在计算系统负载的时候已经计算了*/
    seq_printf(m, "%lu.%02lu %lu.%02lu %lu.%02lu %ld/%d %d\n",
        LOAD_INT(avnrun[0]), LOAD_FRAC(avnrun[0]),
        LOAD_INT(avnrun[1]), LOAD_FRAC(avnrun[1]),
        LOAD_INT(avnrun[2]), LOAD_FRAC(avnrun[2]),
        nr_running(), nr_threads,
        task_active_pid_ns(current)->last_pid);
    return 0;
}

static int loadavg_proc_open(struct inode *inode, struct file *file)
{
    return single_open(file, loadavg_proc_show, NULL);
}

static const struct file_operations loadavg_proc_fops = {
    .open       = loadavg_proc_open,
    .read       = seq_read,
    .llseek     = seq_lseek,
    .release    = single_release,
};

static int __init proc_loadavg_init(void)
{
    proc_create("loadavg", 0, NULL, &loadavg_proc_fops);
    return 0;
}
fs_initcall(proc_loadavg_init);
```
至此就计算完毕了.