Improved Credit Bounds for the Credit-Based Shaper in Time-Sensitive Networking

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***Abstract*—In Time-Sensitive Networking (TSN), it is important to formally prove per-flow latency and backlog bounds. To this end, recent works have applied network calculus and obtained latency bounds from service curves. The latency component of such service curves is directly derived from upper bounds on the values of the credit counters used by the Credit-Based Shaper (CBS), an essential building-block of TSN. In this paper, we derive and formally prove credit upper bounds for the CBS, which improve on existing bounds.**

***Index Terms*—Time-Sensitive Networking (TSN); Audio-Video Bridging (AVB); Credit-Based Shaper (CBS); credit bounds;**

I. Introduction

Time-Sensitive Networking (TSN) is an IEEE 802.1 working group that defines networking mechanisms for supporting real-time data flows with delay guarantees and zero packet loss [1]. TSN targets applications in avionics, automotive and industrial networks, where data loss or delay violation can cause catastrophic damage; therefore, guaranteeing delay is necessary. Other possible application domains of TSN include machine control, media networks, and distributed monitoring, all of which should stick to strict timing rules [2].

One of the main building-blocks of TSN is the Credit-Based Shaper (CBS) that provides rate allocation for a number of priority classes, called Audio-Video Bridging (AVB) classes, by using a credit mechanism (Section II). Recent studies [3]–[5], have obtained delay and backlog bounds for the AVB classes in TSN by using network calculus [6] and service curve characterizations of the CBS. If $\sigma(t)$ is an arrival curve of the input traffic and $\beta(t)$ a service curve of the system, then (i) a delay bound given by network calculus is the horizontal deviation between the two, i.e., $\sup_{s\geq 0}\{\inf\{\tau \geq 0 : \sigma(s) \leq \beta(s+\tau)\}\}$, and (ii) a backlog bound given by network calculus is the vertical deviation between the two, i.e., $\sup_{t\geq 0}\{\beta(t) - \sigma(t)\}$. The works [3]–[5] apply a rate-latency service curve of the CBS, i.e., of the form $\beta(t) = \max(0, R(t-T))$, where R (the rate) and T (the latency) are fixed parameters specific to the network element and to the priority class. The latency T is important for computing the delay and backlog bounds.

Moreover, the latency parameter of such service curves is a linearly increasing function of the applied upper bounds on the credit counters values of the CBS, denoted as credit upper bounds. Therefore, obtaining good credit bounds is a building-block for obtaining good service curves and, subsequently, good delay bounds. Two sets of results were published for credit upper bounds. The first, by J. Cao et al, (“J-bounds”, [7]) provides tight credit upper bounds for the first two AVB classes. Note that since these bounds are tight, they cannot be improved. The second, by H. Daigmorte et al (“H-bounds”, [4]), applies to any number of AVB classes. For the top priority AVB class, J- and H-bounds are identical. For the second priority class, J-bounds are smaller than H-bounds. For third and lower priority classes, only H-bounds are available. The credit bound of a class depends on lower priority classes only via their maximum packet length. Thus, the J-bounds can be applied for the first two priority classes for any system, independently of the total number of classes. For the second priority class, the H-bound is larger than the J-bound, which suggests that the H-bounds can be improved for all classes.

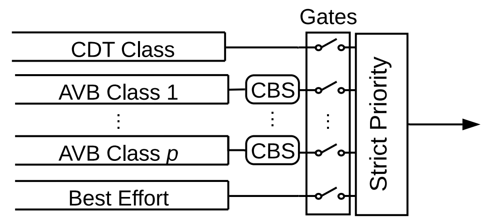

Fig. 1: A TSN scheduler.

In this paper, we derive and formally prove credit upper bounds for the CBS with any number of AVB classes. Specifically, our bounds are the same as J-bounds for the two top priority AVB classes. For all other priority classes, our bounds are better than the only available bounds, i.e. the H-bounds. In addition, in Section IV, we perform numerical evaluations and show that the improvement in the latency parameters of the service curves is significant. The improved credit upper bounds of this paper do not depend on the configuration of the Control-Data Traffic (CDT) of TSN and can be used as building-blocks in TSN studies of delay and backlog bounds.

II. System Model & Existing Credit Bounds

We assume a TSN scheduler, shown in Fig. 1, with the following three elements: 1) a set of queues representing a set of classes including, in decreasing priority, one CDT class, p AVB classes 1, 2, 3, ..., p, and a set of Best Effort (BE) classes; 2) a set of gates, one per queue, such that if a gate is closed, the corresponding queue cannot transmit. A Gate-Control List (GCL) contains the information of the opening/closing times of gates. Note that, there are several integration policies that determine the preemption or non-preemption of CDT over the rest of the classes [4]. The analysis in this paper is valid for all integration policies. This becomes clear in the proof of Theorem 1; 3) a set of CBSs, one per AVB queue, to control the allocated rate of each AVB class. The CBS of an AVB class i has one important parameter, the *idle slope*, $I_i > 0$. The *send slope*, $S_i < 0$, is defined by $I_i - S_i = c$, where c is the line transmission rate. The idle slope is the rate guaranteed to class i. Thus, it is assumed that $\sum_{i=1}^{p} I_i < c$. Packets are scheduled according to the following rules (we repeat here the description in [4]):

R1: If the transmission line is free, the scheduler transmits a packet of the highest priority class that satisfies all the conditions: 1) its queue is not empty; 2) its gate is open; and 3) it has a non-negative credit if it is an AVB class.

R2: The credit of the AVB class i reduces linearly with rate the send slope, S_i, if i transmits.

R3: The credit of the AVB class i increases linearly with rate I_i, when the following conditions hold simultaneously for class i: 1) its gate is open; 2) its queue is not empty; and 3) other AVB or BE classes are transmitting.

R4: The credit of an AVB class remains constant if the corresponding gate is closed and also, during any additional overhead in the case of preemption mode for CDT.

R5: Whenever class i has a positive credit and its queue becomes empty, the credit is set to zero; this is called *credit reset*. If the credit is negative and the queue becomes empty, the credit increases with rate I_i until the zero value.

Let $V_i(t)$ denote the value of the credit counter for AVB class i at time $t \geq 0$. We assume that the system is idle at time 0 and $V_i(0) = 0$. The function $V_i()$ can take positive or negative values and is continuous, except at credit reset times, which by R5, can occur only when the queue of class i becomes empty. At all other times, it linearly increases, decreases or remains constant. Negative credit value is reached when a packet with length larger than $-\frac{cV_i(t)}{S_i}$ starts its transmission at time t. The J-bounds in [7] for the first two AVB classes are,

$$V_1(t) \leq \bar{L}\frac{I_1}{c} := V_1^{\text{max,J}}, \tag{1}$$

$$V_2(t) \leq \frac{I_2}{c}\Big(L_{BE} + L_1 + L_{BE}\frac{I_1}{-S_1}\Big) := V_2^{\text{max,J}}, \tag{2}$$

where L_i and L_{BE} are maximum packet lengths of AVB class i and BE. The H-bounds in [4] apply to any value of p and give, for $i = 1, ..., p$:

$$L_i\frac{S_i}{c} \leq V_i(t) \leq \frac{\bar{L}_i}{c}\sum_{j=1}^{i} I_j - \sum_{j=1}^{i-1} S_j\frac{L_j}{c} := V_i^{\text{max,H}}, \tag{3}$$

where $\bar{L}_i = \max(L_{BE}, L_{>i})$, and $L_{>i}$ is the maximum packet length of the classes having less priority than class i.

For class 1, the J-bounds and H-bounds are identical, i.e., $V_1^{\text{max,J}} = V_1^{\text{max,H}}$. For class 2, we have $V_2^{\text{max,J}} < V_2^{\text{max,H}}$. We also use the following result, proven as Theorem 7 in [4]; for $i = 1...p$:

$$\sum_{j=1}^{i} V_j(t) \leq \frac{\bar{L}_i}{c}\sum_{j=1}^{i} I_j. \tag{4}$$

III. Improved Upper Bound on the Credit of an Arbitrary AVB Class

Theorem 1 (Improved Credit Bounds)**.** *The credit of an AVB class i, $V_i(t)$, is upper bounded, $\forall t \geq 0$, by:*

$$V_i^{\max} = \frac{I_i}{c(c - \sum_{j=1}^{i-1} I_j)}\left(c\bar{L}_i - \sum_{j=1}^{i-1} S_j L_j\right). \tag{5}$$

Remark. The bounds are valid for any number of classes, p, existing in the system as long as $\bar{L}_i$, $\forall i$ is appropriately determined for the corresponding system.

Proof. Consider some fixed time $t \geq 0$ and priority i; we show that $V_i(t) \leq V_i^{\max}$. If $V_i(t) \leq 0$, since $V_i^{\max} \geq 0$, the result follows trivially. Therefore we consider only the case $V_i(t) > 0$. Define time instant $s = \sup\{u \in [0, t] : V_i(u) = 0\}$. Based on the definition of s, $V_i(u) \neq 0,\ \forall u \in (s, t]$. This implies no credit reset in $(s, t]$, i.e., $V_i(\cdot)$ is continuous during this interval. Therefore, $\forall u \in (s, t] : V_i(u) > 0$. Also, CDT either finishes a transmission at s or is not transmitting at s. Indeed, otherwise, since $V_i(s) = 0$, and the credit of i is frozen during the transmission of CDT, it would be true that $V_i(s^+) = 0$ and thus, $s \neq \sup\{u \in [0, t] : V_i(u) = 0\}$.

The class i cannot start a transmission at time s, otherwise, by rule R2, since $V_i(s) = 0$, its credit would decrease to negative values, which contradicts our assumption that $\forall u \in (s, t] : V_i(u) > 0$. Note that since the credit of class i is positive in $(s, t]$, its backlog is also positive in $(s, t]$.

Since $\forall u \in (s, t] : V_i(u) > 0$ and due to rule R1, a class with lower priority than i cannot start a transmission in $(s, t]$. However, in order to consider non-preemptive AVB and BE classes, we must account for the case that a lower priority class has initiated a transmission the latest at s and is still transmitting at s. To do so, we define the time instant t_0, with $s \leq t_0$, as the end of the transmission of the residual of a lower priority packet after time s. The latter is denoted by $l^{LO} \leq \bar{L}_i$. If there is no transmission of a lower priority packet, then $l^{LO} = 0$. If CDT is preemptive then the transmission of l^{LO} can be interrupted and re-continued. Let d^{L0} be the aggregated time period that the credit is frozen within $[s, t_0]$. Then, $t_0 = s + d^{L0} + \frac{l^{LO}}{c}$. If $t_0 > t$, due to rule R3, the credit of class i increases with rate I_i (except during transmission of CDT), therefore $V_i(t) = V_i(s) + I_i(t - s - d^{LO})$. By definition, $V_i(s) = 0$, thus, $V_i(t) = I_i(t - s - d^{LO}) \leq l_i\frac{\bar{L}_i}{c}$ and it follows that $V_i(t) \leq V_i^{\max}$, which ends the proof in this case. Therefore, in the rest of the proof we assume $t_0 \leq t$.

The interval $[t_0, t]$ can be split into a sequence of sub-intervals during which class i alternates between non-transmission and transmission. Let $[t_0, t_1], [t_1, t_2], ..., [t_{n-1}, t_n]$ be such a sequence, with $t_0 \leq t_1 < ... < t_n = t$. We allow $t_0 = t_1$ as this makes it possible to assume that class i does not transmit in the first interval $[t_0, t_1]$ (i.e., if class i starts transmission at time t_0 we set $t_1 = t_0$). It follows that for even intervals $[t_k, t_{k+1}]$, with $k \in \{0, 2, 4, ..., 2\lfloor\frac{n}{2}\rfloor\}$, we have $\frac{d}{dt}V_i(u) \geq 0$, $\forall u \in (t_k, t_{k+1})$. Indeed, during non-transmission, the credit either increases or remains constant, by rules R3 and R4. Conversely, for the odd intervals $[t_k, t_{k+1}]$, with $k \in \{1, 3, 5, ..., 2\lceil \frac{n}{2} \rceil - 1\}$, we have $\frac{d}{dt}V_i(u) < 0$, $\forall u \in (t_k, t_{k+1})$.

Let us define d_k as the aggregated time period that the credit is frozen within the even interval $[t_k, t_{k+1}]$. Next, we study the credit variation for all classes, starting with the interval $[s, t_0]$, then following with even and odd intervals in $(t_0, t]$. In $[s, t_0]$:

- Each class $j < i$ gains credit if it has backlog or negative credit (rule R3), except if CDT transmits, i.e.,

$$V_j(t_0) - V_j(s) \leq I_j(t_0 - s). \tag{6}$$

By summing up for all $j < i$, we have

$$\sum_{j=1}^{i-1} \Big(V_j(t_0) - V_j(s) \Big) \leq \sum_{j=1}^{i-1} I_j (t_0 - s). \tag{7}$$

- Class i gains credit because it has backlog, as explained above, except if CDT transmits, i.e.,

$$V_i(t_0) - V_i(s) = I_i(t_0 - s) - I_i d^{LO}, \tag{8}$$

and since $V_i(s) = 0$ and $t_0 = s + d^{LO} + \frac{l^{LO}}{c}$, we get

$$V_i(t_0) = I_i(t_0 - s - d^{LO}) \leq I_i \frac{l^{LO}}{c} \leq I_i \frac{\bar{L}_i}{c}. \tag{9}$$

For the odd intervals, $[t_{2k-1}, t_{2k}]$, $(1 \leq k \leq \lfloor \frac{n}{2} \rfloor)$:

- Since the credit of class i reduces, the higher priority classes do not transmit within $[t_{2k-1}, t_{2k}]$ and $\forall j < i$: $V_j(t_{2k-1}) \leq 0$. They gain credit if they have positive backlog or negative credit, therefore

$$V_j(t_{2k}) - V_j(t_{2k-1}) \leq I_j(t_{2k} - t_{2k-1}). \tag{10}$$

Summing them up for all $j < i$:

$$\sum_{j=1}^{i-1} \Big(V_j(t_{2k}) - V_j(t_{2k-1}) \Big) \leq \sum_{j=1}^{i-1} I_j (t_{2k} - t_{2k-1}). \tag{11}$$

- The credit of class i reduces due to transmission (R2):

$$V_i(t_{2k}) - V_i(t_{2k-1}) = S_i(t_{2k} - t_{2k-1}). \tag{12}$$

For the even intervals, $[t_{2k}, t_{2k+1}]$, $(0 \leq k \leq \lfloor \frac{n-1}{2} \rfloor)$:

- There exists an AVB class $j < i$ that transmits or all AVB and BE classes wait for CDT (for an aggregated time d_{2k}). Define $a_{j,2k}$ as the aggregated period of time that class j transmits packets in $[t_{2k}, t_{2k+1}]$. Then, by using $I_j - S_j = c$, we obtain

$$V_j(t_{2k+1}) - V_j(t_{2k}) \leq I_j(t_{2k+1} - t_{2k}) - c a_{j,2k} - I_j d_{2k}. \tag{13}$$

Summing up for all $j < i$, and considering that $t_{2k+1} - t_{2k} = d_{2k} + \sum_{j=1}^{i-1} a_{j,2k}$, we obtain

$$\sum_{j=1}^{i-1} \Big(V_j(t_{2k+1}) - V_j(t_{2k}) \Big) \leq$$
$$- \Big(c - \sum_{j=1}^{i-1} I_j \Big) (t_{2k+1} - t_{2k}) + (c - \sum_{j=1}^{i-1} I_j) d_{2k}. \tag{14}$$

- The credit of class i increases or is frozen for an aggregated time d_{2k}, i.e.,

$$V_i(t_{2k+1}) - V_i(t_{2k}) = I_i(t_{2k+1} - t_{2k}) - I_i d_{2k}. \tag{15}$$

Next, we study the credit variation within $[t_0, t_n]$. First we assume that n is odd. By summing up the credit variations for all intervals and all classes $j < i$, we have

$$\sum_{j=1}^{i-1} \Bigg[\Big(V_j(t_1) - V_j(t_0) \Big) + \Big(V_j(t_2) - V_j(t_1) \Big) + ... +$$
$$\Big(V_j(t_{n-1}) - V_j(t_{n-2}) \Big) + \Big(V_j(t_n) - V_j(t_{n-1}) \Big) \Bigg] \leq$$
$$- \Big(c - \sum_{j=1}^{i-1} I_j \Big)(t_1 - t_0) + ... + \sum_{j=1}^{i-1} I_j (t_{n-1} - t_{n-2}) -$$
$$\Big(c - \sum_{j=1}^{i-1} I_j \Big)(t_n - t_{n-1}) + \Big(c - \sum_{j=1}^{i-1} I_j \Big) \sum_{k=0}^{k=\lfloor \frac{n}{2} \rfloor} d_{2k}. \tag{16}$$

Therefore, by setting $\alpha = (t_2 - t_1) + (t_4 - t_3) + ... + (t_{n-1} - t_{n-2})$ and $\Delta t = t_n - t_0 - \sum_{k=0}^{k=\lfloor \frac{n}{2} \rfloor} d_{2k}$, we can write,

$$\sum_{j=1}^{i-1} \Big(V_j(t_n) - V_j(t_0) \Big) \leq -(c - \sum_{j=1}^{i-1} I_j) \Delta t + c\alpha. \tag{17}$$

Next, by summing up the credit variations for all intervals for class i and considering $S_i = I_i - c$,

$$V_i(t_n) - V_i(t_0) = I_i(t_1 - t_0) + (I_i - c)(t_2 - t_1) + ...$$
$$+ I_i(t_n - t_{n-1}) - I_i \sum_{k=0}^{k=\lfloor \frac{n}{2} \rfloor} d_{2k} = I_i \Delta t - c\alpha. \tag{18}$$

By Eq. (4), we obtain

$$\sum_{j=1}^{i-1} V_j(t_0) \leq -V_i(t_0) + \frac{\bar{L}_i}{c} I_i + \frac{\bar{L}_i}{c} \sum_{j=1}^{i-1} I_j. \tag{19}$$

We lower bound the left-hand side of Eq. (17) using the lower bound of Eq. (3) and the bound of Eq. (19); therefore,

$$V_i(t_0) - K \leq c\alpha - (c - \sum_{j=1}^{i-1} I_j) \Delta t, \tag{20}$$

where $K = -\sum_{j=1}^{i-1} L_j \frac{S_j}{c} + \frac{\bar{L}_i}{c} I_i + \frac{\bar{L}_i}{c} \sum_{j=1}^{i-1} I_j \geq 0$. Eq. (20) gives an upper bound on Δt, i.e.,

$$\Delta t \leq \frac{c\alpha + K - V_i(t_0)}{c - \sum_{j=1}^{i-1} I_j}. \tag{21}$$

By using Eq. (21) in Eq. (18), we obtain

$$V_i(t_n) \leq I_i \left(\frac{c\alpha + K - V_i(t_0)}{c - \sum_{j=1}^{i-1} I_j} \right) - c\alpha + V_i(t_0)$$
$$= I_i \left(\frac{K}{c - \sum_{j=1}^{i-1} I_j} \right) + V_i(t_0) \left(\frac{c - \sum_{j=1}^{i-1} I_j - I_i}{c - \sum_{j=1}^{i-1} I_j} \right)$$
$$- c\alpha \left(\frac{c - \sum_{j=1}^{i-1} I_j - I_i}{c - \sum_{j=1}^{i-1} I_j} \right). \tag{22}$$

Next, considering $\sum_{j=1}^{i} I_j < c$, and since by Eq. (9) $V_i(t_0) \leq \frac{\bar{L}_i}{c} I_i$, we obtain

$$V_i(t_n) \leq \frac{I_i}{c\Big(c - \sum_{j=1}^{i-1} I_j\Big)} \left(cK + \bar{L}_i \Big(c - \sum_{j=1}^{i-1} I_j - I_i \Big) \right). \tag{23}$$

By replacing the value of K, the credit of class i at time t_n, where n is odd, is upper bounded by $V_i^{\max}$ given in the statement. If n is even, then

$$V_i(t_n) = V_i(t_{n-1}) + S_i(t_n - t_{n-1}). \tag{24}$$

Since $S_i(t_n - t_{n-1}) \leq 0$, then $V_i(t_n) \leq V_i(t_{n-1})$. As n is even, $n-1$ is odd. We have already found a bound, i.e. $V_i^{\max}$, for t_k when k is odd. Since $t = t_n$, and n is either odd or even, it follows that $V_i(t) \leq V_i^{\max}$. $\square$

For the two top priority classes, the bounds, $V_i^{\max}$ (Eq. (5)), are equal with the J-bounds. Hence, they are tight for the top two priority classes, i.e., for each set of parameters and each class 1, 2, there is a scenario for which the credit counter attains the bound. The proof of tightness is in [7]. Note that, $V_i^{\max}$ depends on lower priority classes only through the parameter $L_{>i}$, and not on their number. Moreover, $V_i^{\max}$ is independent of the CDT configuration in TSN, because when transiting from Eq. (22) to Eq. (23) the quantity α, which depends on the time intervals that CDT transmits, is eliminated. We show that our bounds, $V_i^{\max}$, are always better than the existing bounds, $V_i^{\max,\mathrm{H}}$, for classes $i \geq 3$.

Proposition 1. *For any AVB class $i \geq 3$, $V_i^{\max} < V_i^{\max,\mathrm{H}}$.*

Proof. After some algebra we find

$$V_i^{\max,\mathrm{H}} - V_i^{\max} = \frac{c - \sum_{j=1}^{i} I_j}{c\Big(c - \sum_{j=1}^{i-1} I_j\Big)} \Big(\bar{L}_i \sum_{j=1}^{i-1} I_j - \sum_{j=1}^{i-1} S_j L_j \Big). \tag{25}$$

By hypothesis, $c > \sum_{j=1}^{i} I_j$. Since $I_j > 0$, $S_j < 0$ and $i \geq 2$, it follows that $\bar{L}_i \sum_{j=1}^{i-1} I_j - \sum_{j=1}^{i-1} S_j L^j > 0$, thus the last term of Eq. (25) is strictly positive. $\square$

IV. Numerical Illustration

Consider a TSN scheduler with one CDT, six AVB classes, and one BE class, which is connected to a link with rate $c = 100$ Mbps. The CBS configuration for the AVB classes are set in Table I and for any AVB class i, $S_i = I_i - c$. The CDT is constrained by an affine arrival curve $\sigma(t) = rt + b$ [6] with parameters $r = 12.8$ Kbps and $b = 1.6$ Kb. Also, the maximum packet length for the BE is $L_{BE} = 1.5$ KB. The credit upper bounds for the AVB classes, computed by the H-bounds in (3) and Theorem 1, are shown in Table I. We are interested in classes $3-6$, for which there exist only H-bounds. For the first two classes, our bounds coincide with the tight J-bounds. For the classes $3-6$, the bound by Theorem 1 is less than the H-bound by $65\%, 80\%, 83\%$, and 89%, respectively.

The delay bound of a FIFO system and subsequently, the end-to-end delay bound depend on the credit upper bound, as shown in [3]. Specifically, according to Eq. (22) of [8] (the companion paper of [3]), the latency term of the rate-latency service curve for an AVB class i is computed as:

TABLE I: Credit upper bounds obtained by [4] ($V_i^{\max,\mathrm{H}}$) and Theorem 1 ($V_i^{\max}$). Latency term of service curves, T_i and T_i^{H}, by using $V_i^{\max}$ and $V_i^{\max,\mathrm{H}}$ respectively in Eq. (26).

i	3	4	5	6
L_i (KB)	1	1.2	1	1.5
I_i (Mbps)	15	7	5	3
$V_i^{\max}$ (Bytes)	777.3	647.5	729.7	617.8
$V_i^{\max,H}$ (Bytes)	2250	3205	4396	5391
T_i (μs)	71.9	112.7	166.2.7	226.2
T_i^H (μs)	170.2	478.5	900.4	1819.3

$$T_i = \frac{1}{c-r}\Big(\frac{cV_i^{\mathrm{M}}}{I_i} + b + \frac{rL^{\mathrm{N}}}{c} \Big), \tag{26}$$

where V_i^{M} is a credit upper bound for class i and L^{N} is the maximum packet length of all classes except CDT. In Table I, the last two lines show the latencies T_i (μs) and T_i^H (μs) computed by Eq. (26) when using the credit bounds, $V_i^{\max}$ and $V_i^{\max,H}$, correspondingly. We observe that with our bounds, $V_i^{\max}$, there is a decrease in the service curve latencies of the AVB classes 3 to 6 by $58\%, 76\%, 82\%$, and 88%, respectively, compared with using the H-bounds.

V. Conclusion

In this paper, we have proven significantly better upper bounds for the AVB classes with priority 3 or lower. Our bounds apply for any configuration in TSN. They are essential elements for computing delay and backlog bounds in TSN. Acknowledgement: The authors would like to thank Marc Boyer for his valuable feedback.

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