

(See <https://cs.stanford.edu/~knuth/programs.html> for date.)

**1. Intro.** This program, hacked from ACHAIN4, finds all canonical addition chains of minimum length for a given integer.

There are two command-line parameters. First is a file that contains values of  $l(n)$ , as output by the previous program. Then comes the desired integer  $n$ .

```
#define nmax 10000000 /* should be less than 224 on a 32-bit machine */
#include <stdio.h>
#include <stdlib.h>
unsigned char l[nmax];
int a[128], b[128];
unsigned int undo[128 * 128];
int ptr; /* this many items of the undo stack are in use */
struct {
    int lbp, ubp, lbq, ubq, r, ptrp, ptrq;
} stack[128];
int tail[128], outdeg[128], outsum[128], limit[128];
int down[nmax]; /* a navigation aid discussed below */
FILE *infile;

main(int argc, char *argv[])
{
    register int i, j, n, p, q, r, s, ubp, ubq = 0, lbp, lbq, ptrp, ptrq;
    int lb, nn;

    < Process the command line 2 >;
    < Initialize the down table 7 >;
    for (n = 1; n ≤ nn; n++) {
        < Input the next value, l[n] 3 >;
        < Update the down links 8 >;
    }
    < Backtrack through all solutions 4 >;
}

2. < Process the command line 2 > ≡
if (argc ≠ 3) {
    fprintf(stderr, "Usage: %s infile n\n", argv[0]);
    exit(-1);
}
infile = fopen(argv[1], "r");
if (!infile) {
    fprintf(stderr, "I couldn't open '%s' for reading!\n", argv[1]);
    exit(-2);
}
if (sscanf(argv[2], "%d", &nn) ≠ 1 ∨ nn < 3 ∨ nn ≥ nmax) {
    fprintf(stderr, "The number '%s' was supposed to be between 3 and %d!\n", argv[2], nmax - 1);
    exit(-3);
}
```

This code is used in section 1.

**3.**  $\langle \text{Input the next value, } l[n] \text{ } \mathbf{3} \rangle \equiv$   
 $lb = fgetc(infile) - '\_';$   $\text{ /* } fgetc \text{ will return a negative value after EOF */}$   
**if**  $(lb < 0 \vee (n > 1 \wedge lb > l[n-1] + 1))$  {  
 $fprintf(stderr, \text{"Input\_file\_has\_the\_wrong\_value\_"}(\%d)\_\text{for\_l}[\%d]!\backslash n", lb, n);$   
 $exit(-4);$   
 }  
 $l[n] = lb;$

This code is used in section [1](#).

#### 4. The interesting part.

```

⟨ Backtrack through all solutions 4 ⟩ ≡
  a[0] = b[0] = 1, a[1] = b[1] = 2;
  n = nn, lb = l[n];
  for (i = 0; i ≤ lb; i++) outdeg[i] = outsum[i] = 0;
  a[lb] = b[lb] = n;
  for (i = 2; i < lb; i++) a[i] = a[i - 1] + 1, b[i] = b[i - 1] ≪ 1;
  for (i = lb - 1; i ≥ 2; i--) {
    if ((a[i] ≪ 1) < a[i + 1]) a[i] = (a[i + 1] + 1) ≫ 1;
    if (b[i] ≥ b[i + 1]) b[i] = b[i + 1] - 1;
  }
  ⟨ Try to fix the rest of the chain, and output all the solutions 9 ⟩;

```

This code is used in section 1.

5. One of the key operations we need is to increase  $p$  to the smallest element  $p' > p$  that has  $l[p'] < s$ , given that  $l[p] < s$ . Since  $l[p+1] \leq l[p] + 1$ , we can do this quickly by first setting  $p \leftarrow p + 1$ ; then, if  $l[p] = s$ , we set  $p \leftarrow \text{down}[p]$ , where  $\text{down}[p]$  is the smallest  $p' > p$  that has  $l[p'] < l[p]$ .

The links  $\text{down}[p]$  can be prepared as we go, starting them off at  $\infty$  and updating them whenever we learn a new value of  $l[n]$ .

Instead of using infinite links, however, we can save space by temporarily letting  $\text{down}[p] = p''$  in such cases, where  $p''$  is the largest element *less than*  $p$  whose  $\text{down}$  link is effectively infinite. These temporary links tell us exactly what we need to know during the updating process. And we can distinguish them from “real”  $\text{down}$  links by pretending that  $\text{down}[p] = \infty$  whenever  $\text{down}[p] \leq p$ .

```

⟨ Given that  $l[p] < s$ , increase  $p$  to the next such element 5 ⟩ ≡
{
  p++;
  if ( $l[p] \equiv s$ )  $p = (\text{down}[p] > p ? \text{down}[p] : nmax)$ ;
}

```

This code is used in section 11.

```

6. ⟨ Given that  $l[p] \geq s$ , increase  $p$  to the next element with  $l[p] < s$  6 ⟩ ≡
do {
  if ( $\text{down}[p] > p$ )  $p = \text{down}[p]$ ;
  else {
     $p = nmax$ ; break;
  }
} while ( $l[p] \geq s$ );

```

This code is used in sections 10 and 11.

```

7. ⟨ Initialize the  $\text{down}$  table 7 ⟩ ≡
for ( $n = 1$ ;  $n \leq nn$ ;  $n++$ )  $\text{down}[n] = n - 1$ ;

```

This code is used in section 1.

8. I can't help exclaiming that this little algorithm is quite pretty.

```

⟨ Update the  $\text{down}$  links 8 ⟩ ≡
if ( $l[n] < l[n - 1]$ ) {
  for ( $p = \text{down}[n]$ ;  $l[p] > l[n]$ ;  $p = q$ )  $q = \text{down}[p]$ ,  $\text{down}[p] = n$ ;
   $\text{down}[n] = p$ ;
}

```

This code is used in section 1.

9.  $\langle$  Try to fix the rest of the chain, and output all the solutions 9  $\rangle \equiv$   
 $ptr = 0;$  /\* clear the *undo* stack \*/  
**for** ( $r = s = lb; s > 2; s--$ ) {  
  **if** ( $outdeg[s] \equiv 1$ )  $limit[s] = a[s] - tail[outsum[s]]$ ; **else**  $limit[s] = a[s] - 1$ ;  
  /\* the max feasible  $p$  \*/  
  **if** ( $limit[s] > b[s - 1]$ )  $limit[s] = b[s - 1]$ ;  
   $\langle$  Set  $p$  to its smallest feasible value, and  $q = a[s] - p$  10  $\rangle$ ;  
  **while** ( $p \leq limit[s]$ ) {  
     $\langle$  Find bounds ( $lb_p, ub_p$ ) and ( $lb_q, ub_q$ ) on where  $p$  and  $q$  can be inserted; but go to *failpq* if they  
    can't both be accommodated 14  $\rangle$ ;  
     $ptrp = ptr$ ;  
    **for** ( ;  $ubp \geq lb_p; ubp--$ ) {  
       $\langle$  Put  $p$  into the chain at location  $ubp$ ; **goto** *failp* if there's a problem 16  $\rangle$ ;  
      **if** ( $p \equiv q$ ) **goto** *happiness*;  
      **if** ( $ubq \geq ubp$ )  $ubq = ubp - 1$ ;  
       $ptrq = ptr$ ;  
      **for** ( ;  $ubq \geq lb_q; ubq--$ ) {  
         $\langle$  Put  $q$  into the chain at location  $ubq$ ; **goto** *failq* if there's a problem 18  $\rangle$ ;  
      *happiness*:  $\langle$  Put local variables on the stack and update outdegrees 12  $\rangle$ ;  
      **goto** *onward*; /\* now  $a[s]$  is covered; try to cover  $a[s - 1]$  \*/  
      *backup*:  $s++$ ;  
      **if** ( $s > lb$ ) **goto** *impossible*;  
       $\langle$  Restore local variables from the stack and downdate outdegrees 13  $\rangle$ ;  
      **if** ( $p \equiv q$ ) **goto** *failp*;  
      *failq*: **while** ( $ptr > ptrq$ )  $\langle$  Undo a change 15  $\rangle$ ;  
      } /\* end loop on  $ubq$  \*/  
      *failp*: **while** ( $ptr > ptrp$ )  $\langle$  Undo a change 15  $\rangle$ ;  
      } /\* end loop on  $ubp$  \*/  
      *failpq*:  $\langle$  Advance  $p$  to the next smallest feasible value, and set  $q = a[s] - p$  11  $\rangle$ ;  
      } /\* end loop on  $p$  \*/  
    **goto** *backup*;  
    *onward*: **continue**;  
  } /\* end loop on  $s$  \*/  
   $\langle$  Print a solution 20  $\rangle$ ;  
  **goto** *backup*;  
*impossible*:

This code is used in section 4.

**10.** At this point we have  $a[k] = b[k]$  for all  $r \leq k \leq lb$ .

```

⟨ Set  $p$  to its smallest feasible value, and  $q = a[s] - p$  10 ⟩ ≡
  if ( $a[s] \& 1$ ) { /* necessarily  $p \neq q$  */
    unequal: if ( $outdeg[s-1] \equiv 0$ )  $q = a[s]/3$ ; else  $q = a[s] \gg 1$ ;
    if ( $q > b[s-2]$ )  $q = b[s-2]$ ;
     $p = a[s] - q$ ;
    if ( $l[p] \geq s$ ) {
      ⟨ Given that  $l[p] \geq s$ , increase  $p$  to the next element with  $l[p] < s$  6 ⟩;
       $q = a[s] - p$ ;
    }
  } else {
     $p = q = a[s] \gg 1$ ;
    if ( $l[p] \geq s$ ) goto unequal; /* a rare case like  $l[191] = l[382]$  */
  }
  if ( $p > limit[s]$ ) goto backup;
  for ( ;  $r > 2 \wedge a[r-1] \equiv b[r-1]$ ;  $r--$  ) ;
  if ( $p > b[r-1]$ ) { /* now  $r < s$ , since  $p \leq b[s-1]$  */
    while ( $p > a[r]$ )  $r++$ ; /* this step keeps  $r < s$ , since  $a[s-1] = b[s-1]$  */
     $p = a[r], q = a[s] - p$ ;
  } else if ( $q < p \wedge q > b[r-2]$ ) {
    if ( $a[r] \leq a[s] - b[r-2]$ )  $p = a[r], q = b[s] - p$ ;
    else  $q = b[r-2], p = a[s] - q$ ;
  }

```

This code is used in section 9.

11.  $\langle \text{Advance } p \text{ to the next smallest feasible value, and set } q = a[s] - p \text{ 11} \rangle \equiv$

```

if ( $p \equiv q$ ) {
  if ( $\text{outdeg}[s-1] \equiv 0$ )  $q = (a[s]/3) + 1$ ;    /* will be decreased momentarily */
  if ( $q > b[s-2]$ )  $q = b[s-2]$ ; else  $q--$ ;
   $p = a[s] - q$ ;
  if ( $l[p] \geq s$ ) {
     $\langle \text{Given that } l[p] \geq s, \text{ increase } p \text{ to the next element with } l[p] < s \text{ 6} \rangle$ ;
     $q = a[s] - p$ ;
  }
} else {
   $\langle \text{Given that } l[p] < s, \text{ increase } p \text{ to the next such element 5} \rangle$ ;
   $q = a[s] - p$ ;
}
if ( $q > 2$ ) {
  if ( $a[s-1] \equiv b[s-1]$ ) {    /* maybe  $p$  has to be present already */
    doublecheck: while ( $p < a[r] \wedge a[r-1] \equiv b[r-1]$ )  $r--$ ;
    if ( $p > b[r-1]$ ) {
      while ( $p > a[r]$ )  $r++$ ;
       $p = a[r], q = a[s] - p$ ;    /* possibly  $r = s$  now */
    } else if ( $q > b[r-2]$ ) {
      if ( $a[r] \leq a[s] - b[r-2]$ )  $p = a[r], q = b[s] - p$ ;
      else  $q = b[r-2], p = a[s] - q$ ;
    }
  }
  if ( $ubq \geq s$ )  $ubq = s - 1$ ;
  while ( $q \geq a[ubq + 1]$ )  $ubq++$ ;
  while ( $q < a[ubq]$ )  $ubq--$ ;
  if ( $q > b[ubq]$ ) {
     $q = b[ubq], p = a[s] - q$ ;
    if ( $a[s-1] \equiv b[s-1]$ ) goto doublecheck;
  }
}

```

This code is used in section 9.

12.  $\langle \text{Put local variables on the stack and update outdegrees 12} \rangle \equiv$

```

 $\text{tail}[s] = q, \text{stack}[s].r = r$ ;
 $\text{outdeg}[ubp]++, \text{outsum}[ubp] += s$ ;
 $\text{outdeg}[ubq]++, \text{outsum}[ubq] += s$ ;
 $\text{stack}[s].lbp = lbp, \text{stack}[s].ubp = ubp$ ;
 $\text{stack}[s].lbq = lbq, \text{stack}[s].ubq = ubq$ ;
 $\text{stack}[s].ptrp = ptrp, \text{stack}[s].ptrq = ptrq$ ;

```

This code is used in section 9.

13.  $\langle \text{Restore local variables from the stack and downdate outdegrees 13} \rangle \equiv$

```

 $\text{ptrq} = \text{stack}[s].ptrq, \text{ptrp} = \text{stack}[s].ptrp$ ;
 $\text{lbq} = \text{stack}[s].lbq, \text{ubq} = \text{stack}[s].ubq$ ;
 $\text{lbp} = \text{stack}[s].lbp, \text{ubp} = \text{stack}[s].ubp$ ;
 $\text{outdeg}[ubq]--, \text{outsum}[ubq] -= s$ ;
 $\text{outdeg}[ubp]--, \text{outsum}[ubp] -= s$ ;
 $q = \text{tail}[s], p = a[s] - q, r = \text{stack}[s].r$ ;

```

This code is used in section 9.

14. After the test in this step is passed, we'll have  $ubp > ubq$  and  $lbp > lbq$ .

⟨ Find bounds  $(lbp, ubp)$  and  $(lbq, ubq)$  on where  $p$  and  $q$  can be inserted; but go to *failpq* if they can't both be accommodated 14 ⟩  $\equiv$

```

if ( $l[p] \geq s$ ) goto failpq;
 $lbp = l[p]$ ;
while ( $b[lbp] < p$ )  $lbp++$ ;
if ( $(p \& 1) \wedge p > b[lbp - 2] + b[lbp - 1]$ ) {
  if ( $++lbp \geq s$ ) goto failpq;
}
if ( $a[lbp] > p$ ) goto failpq;
for ( $ubp = lbp$ ;  $a[ubp + 1] \leq p$ ;  $ubp++$ ) ;
if ( $ubp \equiv s - 1$ )  $lbp = ubp$ ;
if ( $p \equiv q$ )  $lbq = lbp, ubq = ubp$ ;
else {
   $lbq = l[q]$ ;
  if ( $lbq \geq ubp$ ) goto failpq;
  while ( $b[lbq] < q$ )  $lbq++$ ;
  if ( $a[lbq] < b[lbq]$ ) {
    if ( $(q \& 1) \wedge q > b[lbq - 2] + b[lbq - 1]$ )  $lbq++$ ;
    if ( $lbq \geq ubp$ ) goto failpq;
    if ( $a[lbq] > q$ ) goto failpq;
    if ( $lbp \leq lbq$ )  $lbp = lbq + 1$ ;
    while ( $(q \ll (lbp - lbq)) < p$ )
      if ( $++lbp > ubp$ ) goto failpq;
  }
  for ( $ubq = lbq$ ;  $a[ubq + 1] \leq q \wedge (q \ll (ubp - ubq - 1)) \geq p$ ;  $ubq++$ ) ;
}

```

This code is used in section 9.

15. The undoing mechanism is very simple: When changing  $a[j]$ , we put  $(j \ll 24) + x$  on the *undo* stack, where  $x$  was the former value. Similarly, when changing  $b[j]$ , we stack the value  $(1 \ll 31) + (j \ll 24) + x$ .

```

#define newa( $j, y$ )  $undo[ptr++] = (j \ll 24) + a[j], a[j] = y$ 
#define newb( $j, y$ )  $undo[ptr++] = (1 \ll 31) + (j \ll 24) + b[j], b[j] = y$ 
⟨ Undo a change 15 ⟩  $\equiv$ 
{
   $i = undo[--ptr]$ ;
  if ( $i \geq 0$ )  $a[i \gg 24] = i \& \#ffffff$ ;
  else  $b[(i \& \#3fffffff) \gg 24] = i \& \#ffffff$ ;
}

```

This code is used in section 9.

**16.** At this point we know that  $a[ubp] \leq p \leq b[ubp]$ .

$\langle$  Put  $p$  into the chain at location  $ubp$ ; **goto** *failp* if there's a problem 16  $\rangle \equiv$

```

if ( $a[ubp] \neq p$ ) {
  newa( $ubp, p$ );
  for ( $j = ubp - 1$ ; ( $a[j] \ll 1$ ) <  $a[j + 1]$ ;  $j--$ ) {
     $i = (a[j + 1] + 1) \gg 1$ ;
    if ( $i > b[j]$ ) goto failp;
    newa( $j, i$ );
  }
  for ( $j = ubp + 1$ ;  $a[j] \leq a[j - 1]$ ;  $j++$ ) {
     $i = a[j - 1] + 1$ ;
    if ( $i > b[j]$ ) goto failp;
    newa( $j, i$ );
  }
}
if ( $b[ubp] \neq p$ ) {
  newb( $ubp, p$ );
  for ( $j = ubp - 1$ ;  $b[j] \geq b[j + 1]$ ;  $j--$ ) {
     $i = b[j + 1] - 1$ ;
    if ( $i < a[j]$ ) goto failp;
    newb( $j, i$ );
  }
  for ( $j = ubp + 1$ ;  $b[j] > b[j - 1] \ll 1$ ;  $j++$ ) {
     $i = b[j - 1] \ll 1$ ;
    if ( $i < a[j]$ ) goto failp;
    newb( $j, i$ );
  }
}

```

$\langle$  Make forced moves if  $p$  has a special form 17  $\rangle$ ;

This code is used in section 9.



**17.** If, say, we've just set  $a[8] = b[8] = 132$ , special considerations apply, because the only addition chains of length 8 for 132 are

1, 2, 4, 8, 16, 32, 64, 128, 132;  
 1, 2, 4, 8, 16, 32, 64, 68, 132;  
 1, 2, 4, 8, 16, 32, 64, 66, 132;  
 1, 2, 4, 8, 16, 32, 34, 66, 132;  
 1, 2, 4, 8, 16, 32, 33, 66, 132;  
 1, 2, 4, 8, 16, 17, 33, 66, 132.

The values of  $a[4]$  and  $b[4]$  must therefore be 16; and then, of course, we also must have  $a[3] = b[3] = 8$ , etc. Similar reasoning applies whenever we set  $a[j] = b[j] = 2^j + 2^k$  for  $k \leq j - 4$ .

Such cases may seem extremely special. But my hunch is that they are important, because efficient chains need such values. When we try to prove that no efficient chain exists, we want to show that such values can't be present. Numbers with small  $l[p]$  are harder to rule out, so it should be helpful to penalize them.

```

⟨ Make forced moves if  $p$  has a special form 17 ⟩ ≡
   $i = p - (1 \ll (ubp - 1));$ 
  if ( $i \wedge ((i \& (i - 1)) \equiv 0) \wedge (i \ll 4) < p$ ) {
    for ( $j = ubp - 2; (i \& 1) \equiv 0; i \gg= 1, j--$ ) ;
    if ( $b[j] < (1 \ll j)$ ) goto failp;
    for ( ;  $a[j] < (1 \ll j); j--$ ) newa( $j, 1 \ll j$ );
  }

```

This code is used in section 16.

18. At this point we had better not assume that  $a[ubq] \leq q \leq b[ubq]$ , because  $p$  has just been inserted. That insertion can mess up the bounds that we looked at when  $lbq$  and  $ubq$  were computed.

⟨ Put  $q$  into the chain at location  $ubq$ ; **goto** *failq* if there's a problem 18 ⟩  $\equiv$

```

if ( $a[ubq] \neq q$ ) {
  if ( $a[ubq] > q$ ) goto failq;
  newa( $ubq, q$ );
  for ( $j = ubq - 1$ ; ( $a[j] \ll 1$ ) <  $a[j + 1]$ ;  $j--$ ) {
     $i = (a[j + 1] + 1) \gg 1$ ;
    if ( $i > b[j]$ ) goto failq;
    newa( $j, i$ );
  }
  for ( $j = ubq + 1$ ;  $a[j] \leq a[j - 1]$ ;  $j++$ ) {
     $i = a[j - 1] + 1$ ;
    if ( $i > b[j]$ ) goto failq;
    newa( $j, i$ );
  }
}
if ( $b[ubq] \neq q$ ) {
  if ( $b[ubq] < q$ ) goto failq;
  newb( $ubq, q$ );
  for ( $j = ubq - 1$ ;  $b[j] \geq b[j + 1]$ ;  $j--$ ) {
     $i = b[j + 1] - 1$ ;
    if ( $i < a[j]$ ) goto failq;
    newb( $j, i$ );
  }
  for ( $j = ubq + 1$ ;  $b[j] > b[j - 1] \ll 1$ ;  $j++$ ) {
     $i = b[j - 1] \ll 1$ ;
    if ( $i < a[j]$ ) goto failq;
    newb( $j, i$ );
  }
}
⟨ Make forced moves if  $q$  has a special form 19 ⟩;
```

This code is used in section 9.

19. ⟨ Make forced moves if  $q$  has a special form 19 ⟩  $\equiv$

```

 $i = q - (1 \ll (ubq - 1));$ 
if ( $(i \wedge ((i \& (i - 1)) \equiv 0) \wedge (i \ll 4) < q)$ ) {
  for ( $j = ubq - 2$ ; ( $i \& 1$ )  $\equiv 0$ ;  $i \gg= 1, j--$ ) ;
  if ( $b[j] < (1 \ll j)$ ) goto failq;
  for ( ;  $a[j] < (1 \ll j)$ ;  $j--$ ) newa( $j, 1 \ll j$ );
}

```

This code is used in section 18.

20. ⟨ Print a solution 20 ⟩  $\equiv$

```

for ( $j = 0$ ;  $j \leq lb$ ;  $j++$ ) printf("□%d",  $a[j]$ );
printf("\\n");

```

This code is used in section 9.

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*tail*: [1](#), [9](#), [12](#), [13](#).  
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*ubq*: [1](#), [9](#), [11](#), [12](#), [13](#), [14](#), [18](#), [19](#).  
*undo*: [1](#), [9](#), [15](#).  
*unequal*: [10](#).

- ⟨ Advance  $p$  to the next smallest feasible value, and set  $q = a[s] - p$  11 ⟩    Used in section 9.
- ⟨ Backtrack through all solutions 4 ⟩    Used in section 1.
- ⟨ Find bounds  $(lb_p, ub_p)$  and  $(lb_q, ub_q)$  on where  $p$  and  $q$  can be inserted; but go to *failpq* if they can't both be accommodated 14 ⟩    Used in section 9.
- ⟨ Given that  $l[p] < s$ , increase  $p$  to the next such element 5 ⟩    Used in section 11.
- ⟨ Given that  $l[p] \geq s$ , increase  $p$  to the next element with  $l[p] < s$  6 ⟩    Used in sections 10 and 11.
- ⟨ Initialize the *down* table 7 ⟩    Used in section 1.
- ⟨ Input the next value,  $l[n]$  3 ⟩    Used in section 1.
- ⟨ Make forced moves if  $p$  has a special form 17 ⟩    Used in section 16.
- ⟨ Make forced moves if  $q$  has a special form 19 ⟩    Used in section 18.
- ⟨ Print a solution 20 ⟩    Used in section 9.
- ⟨ Process the command line 2 ⟩    Used in section 1.
- ⟨ Put local variables on the stack and update outdegrees 12 ⟩    Used in section 9.
- ⟨ Put  $p$  into the chain at location  $ubp$ ; **goto** *failp* if there's a problem 16 ⟩    Used in section 9.
- ⟨ Put  $q$  into the chain at location  $ubq$ ; **goto** *failq* if there's a problem 18 ⟩    Used in section 9.
- ⟨ Restore local variables from the stack and downdate outdegrees 13 ⟩    Used in section 9.
- ⟨ Set  $p$  to its smallest feasible value, and  $q = a[s] - p$  10 ⟩    Used in section 9.
- ⟨ Try to fix the rest of the chain, and output all the solutions 9 ⟩    Used in section 4.
- ⟨ Undo a change 15 ⟩    Used in section 9.
- ⟨ Update the *down* links 8 ⟩    Used in section 1.

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