Sorting integer arrays: security, speed, and verification

D. J. Bernstein

University of Illinois at Chicago,
Ruhr-University Bochum

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From: Alice


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Bob assumes this message is something Alice actually sent.

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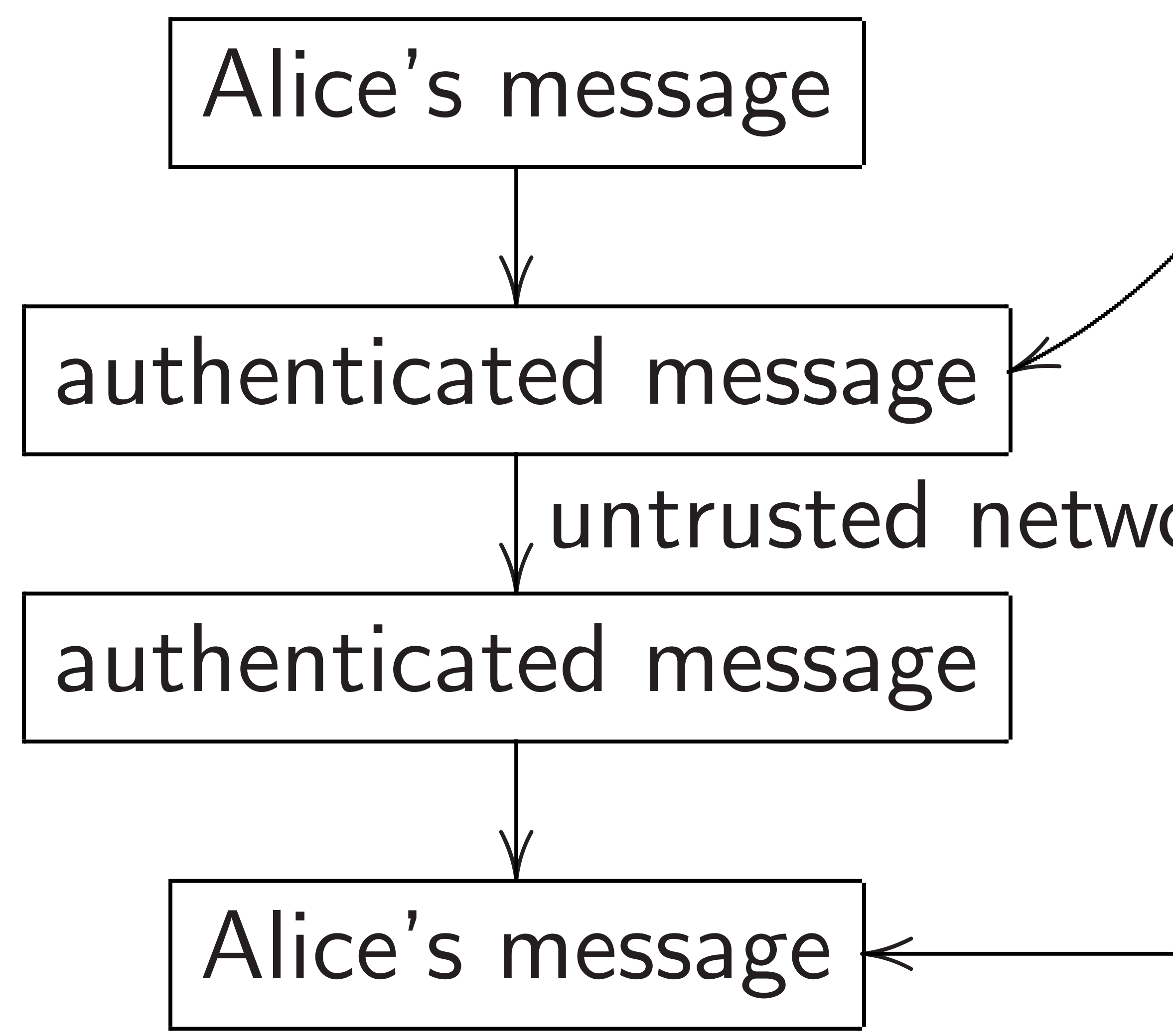

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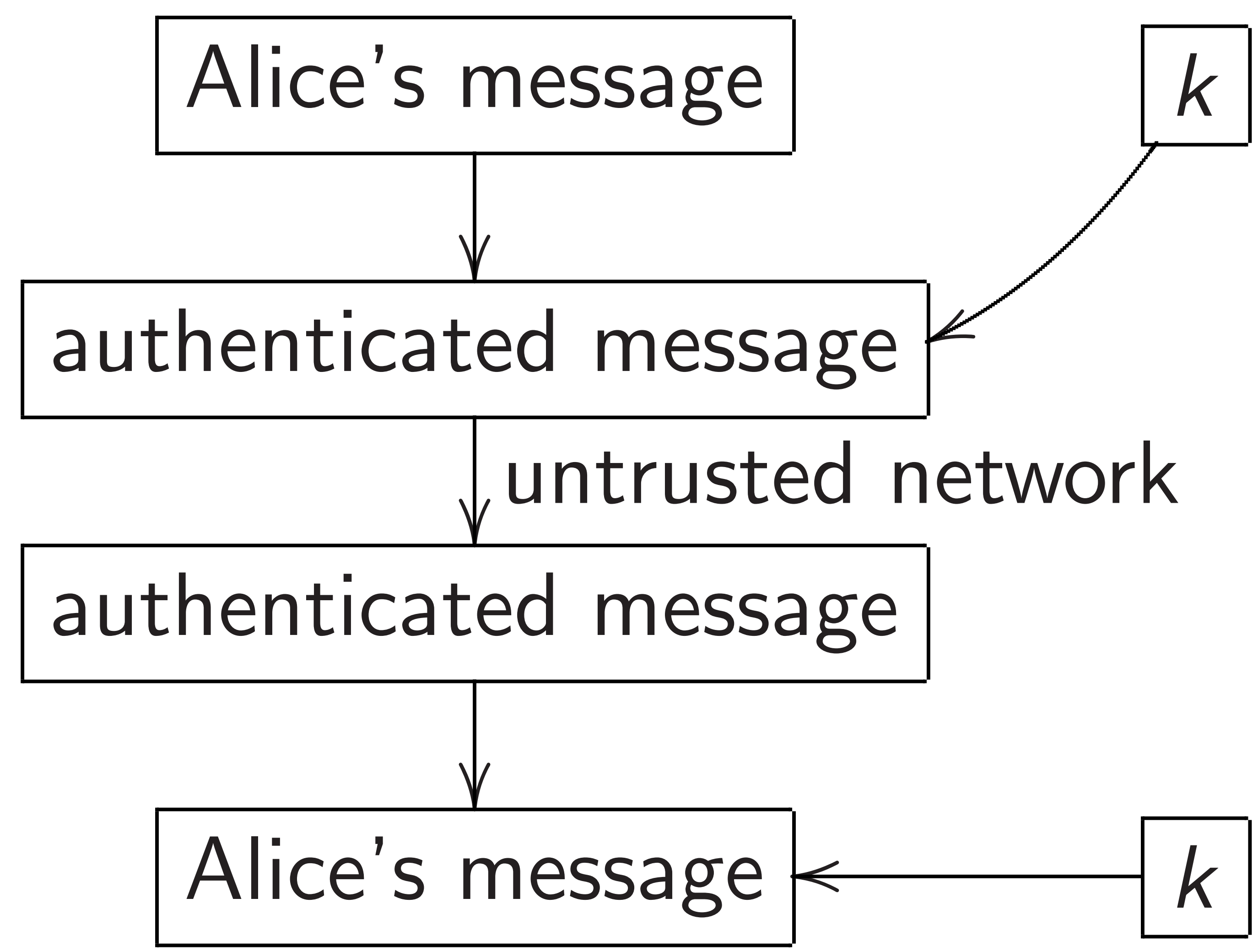

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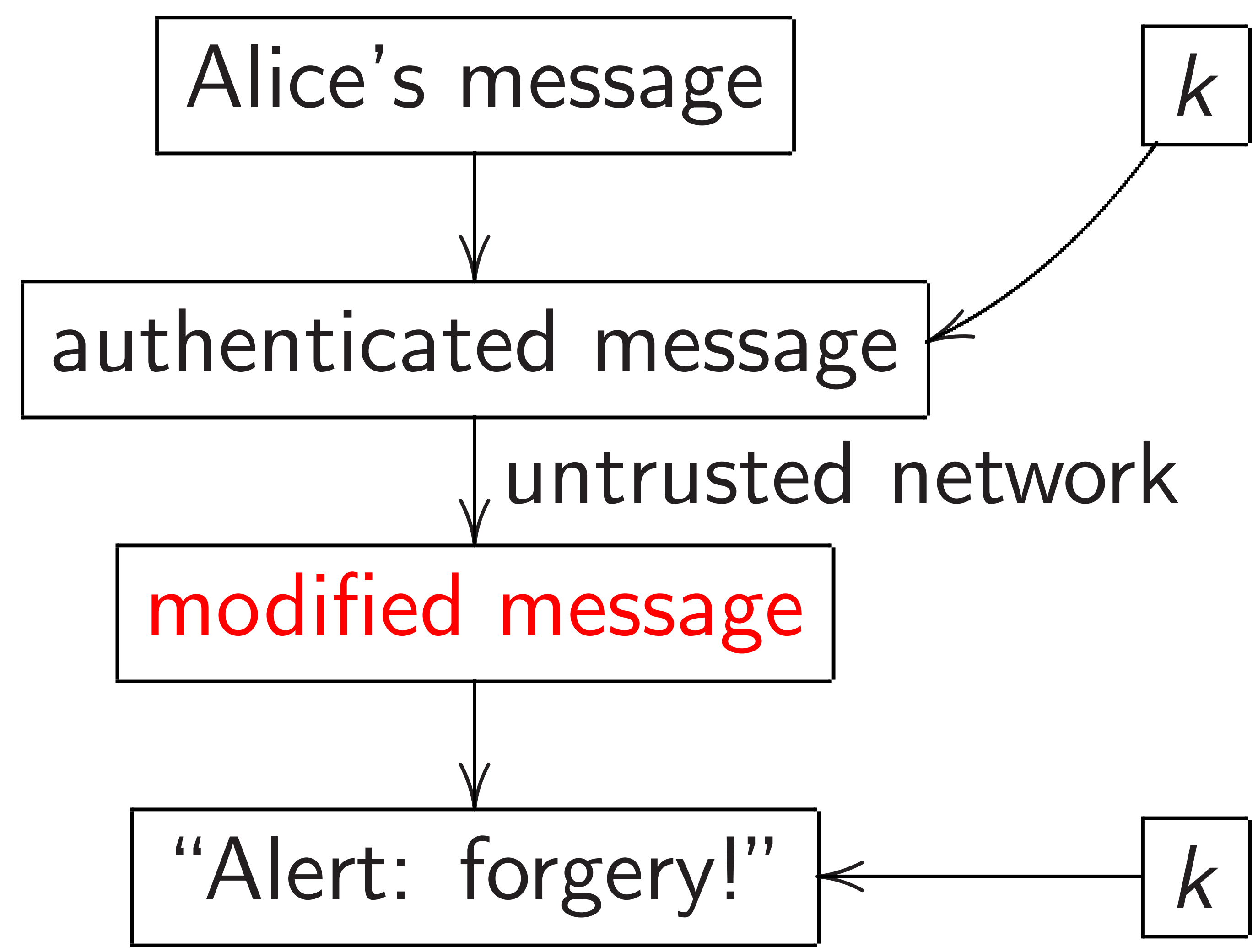

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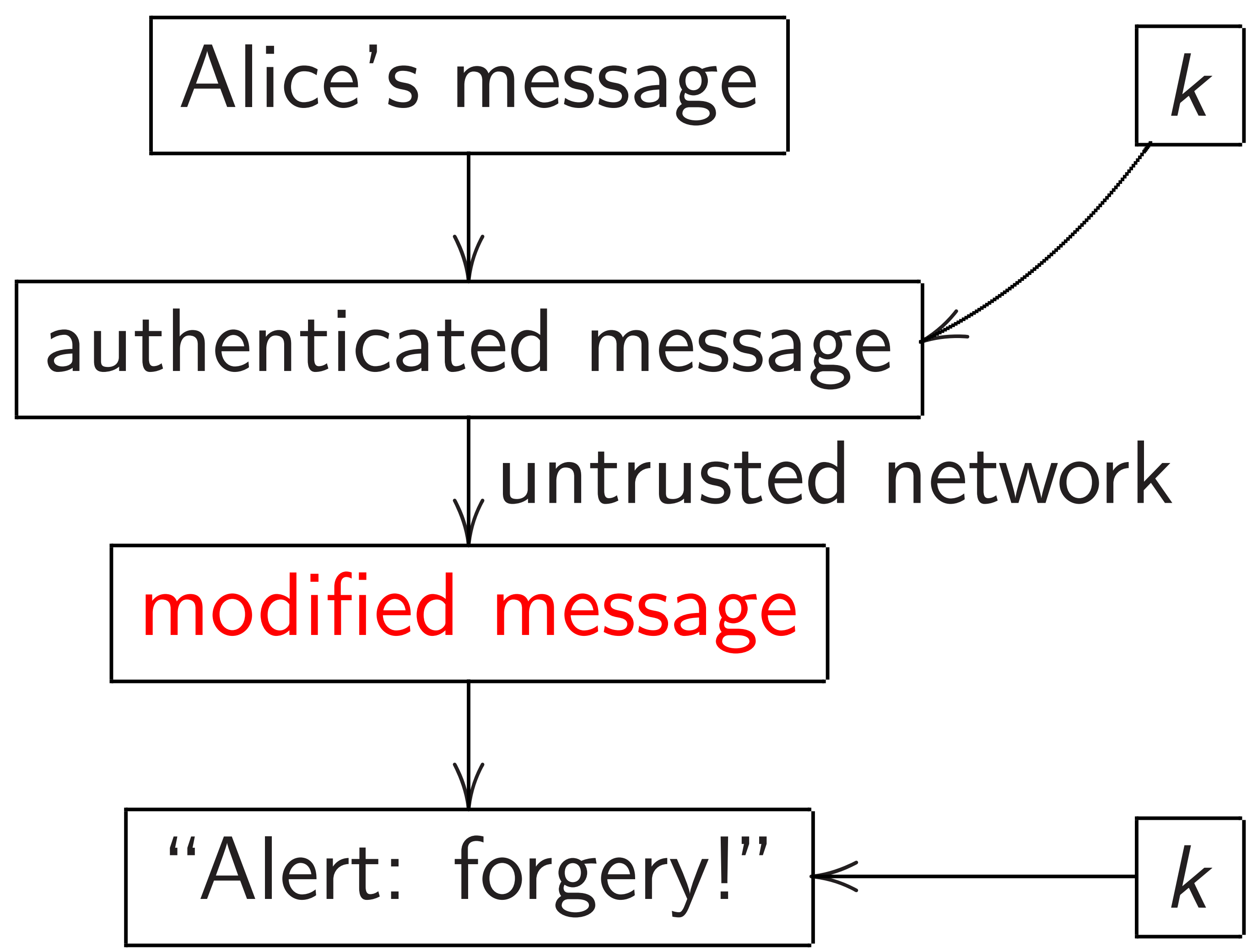

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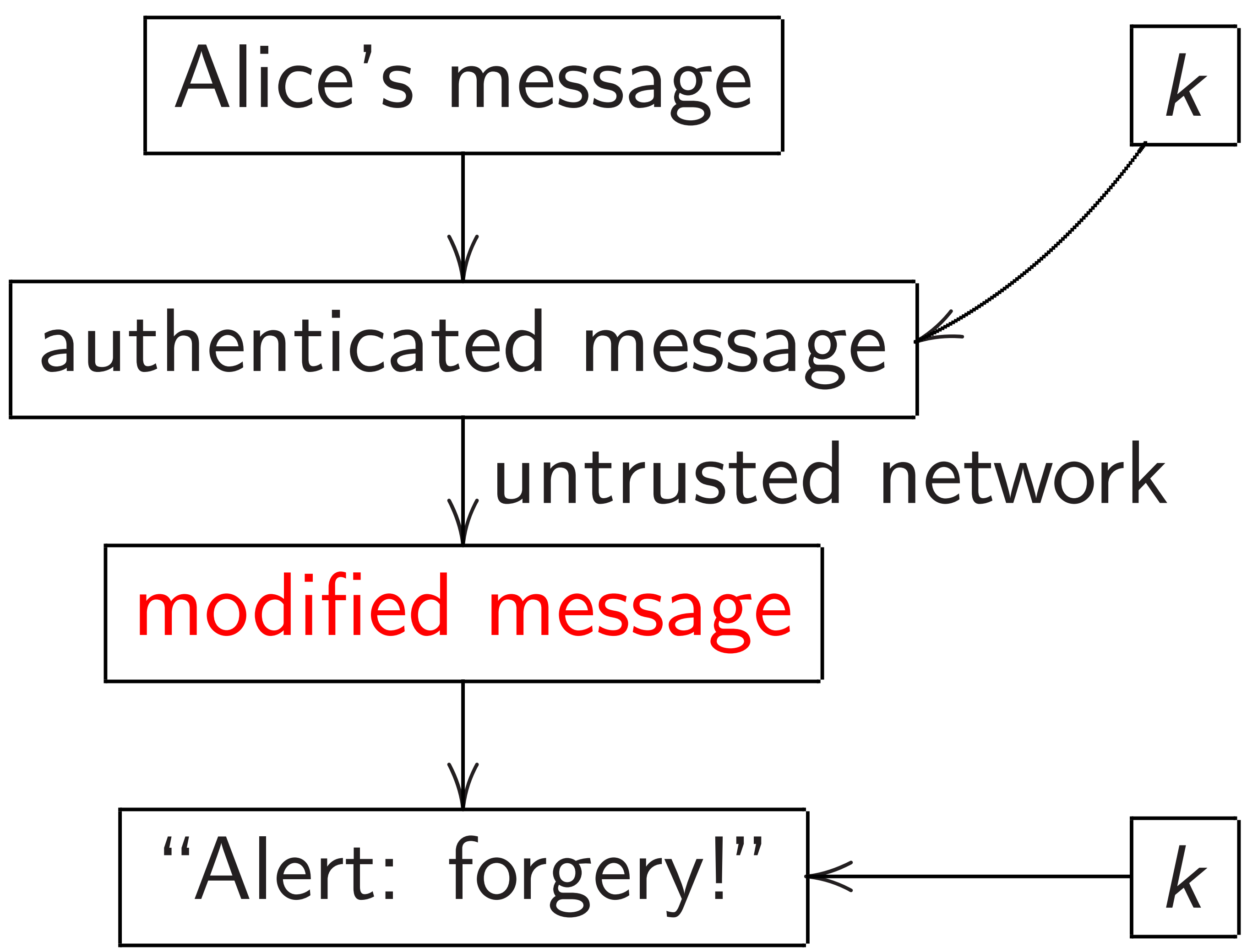

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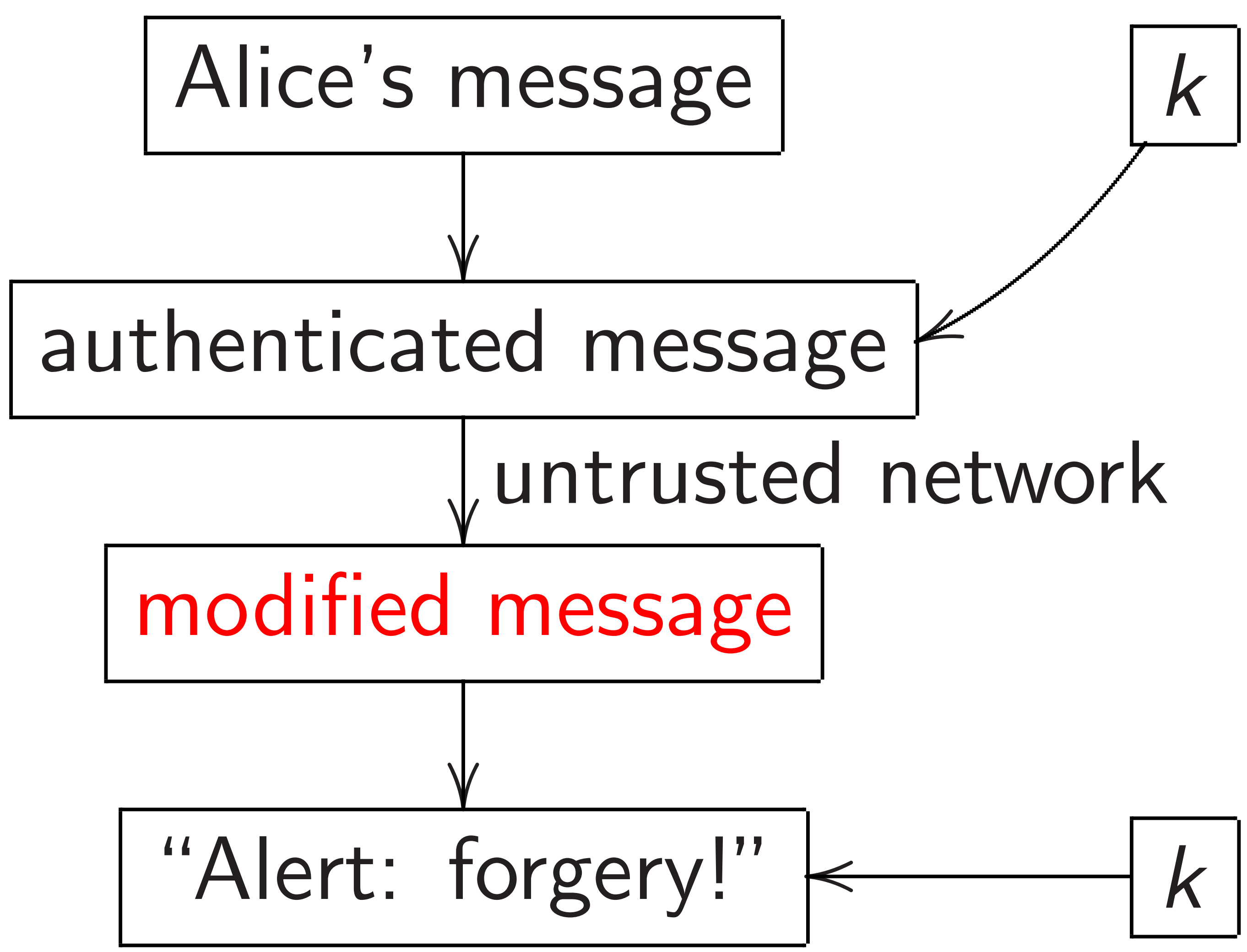

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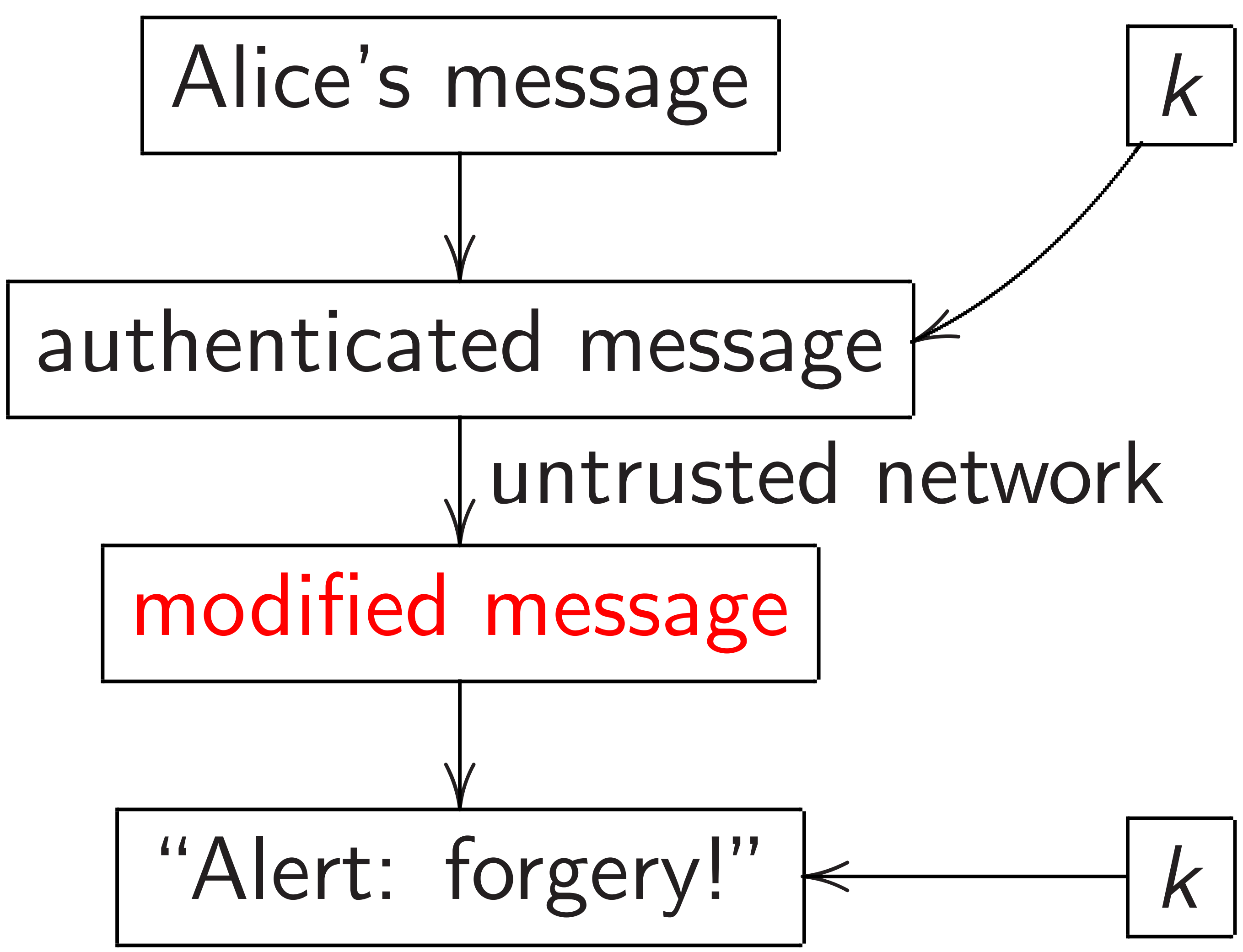

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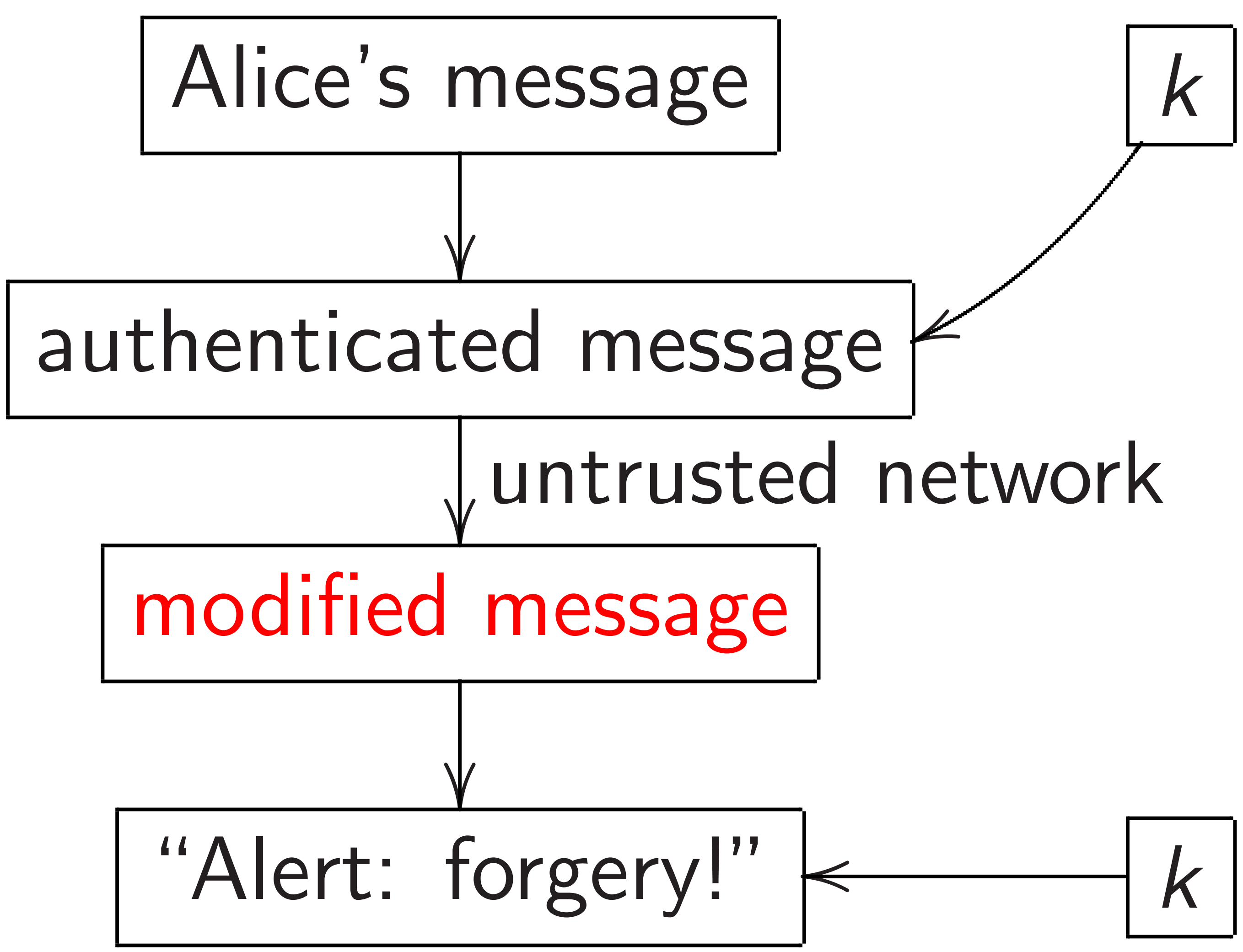

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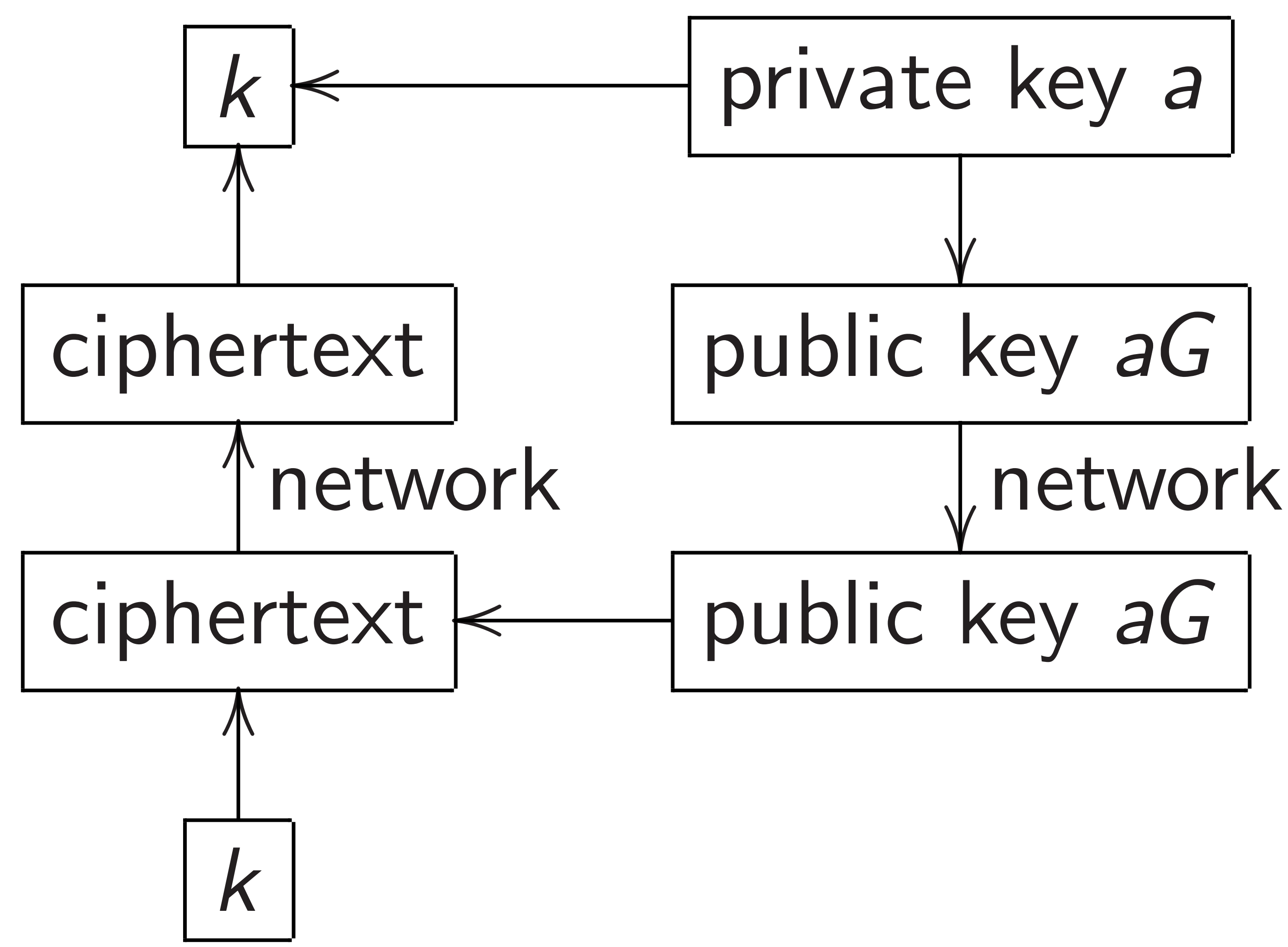

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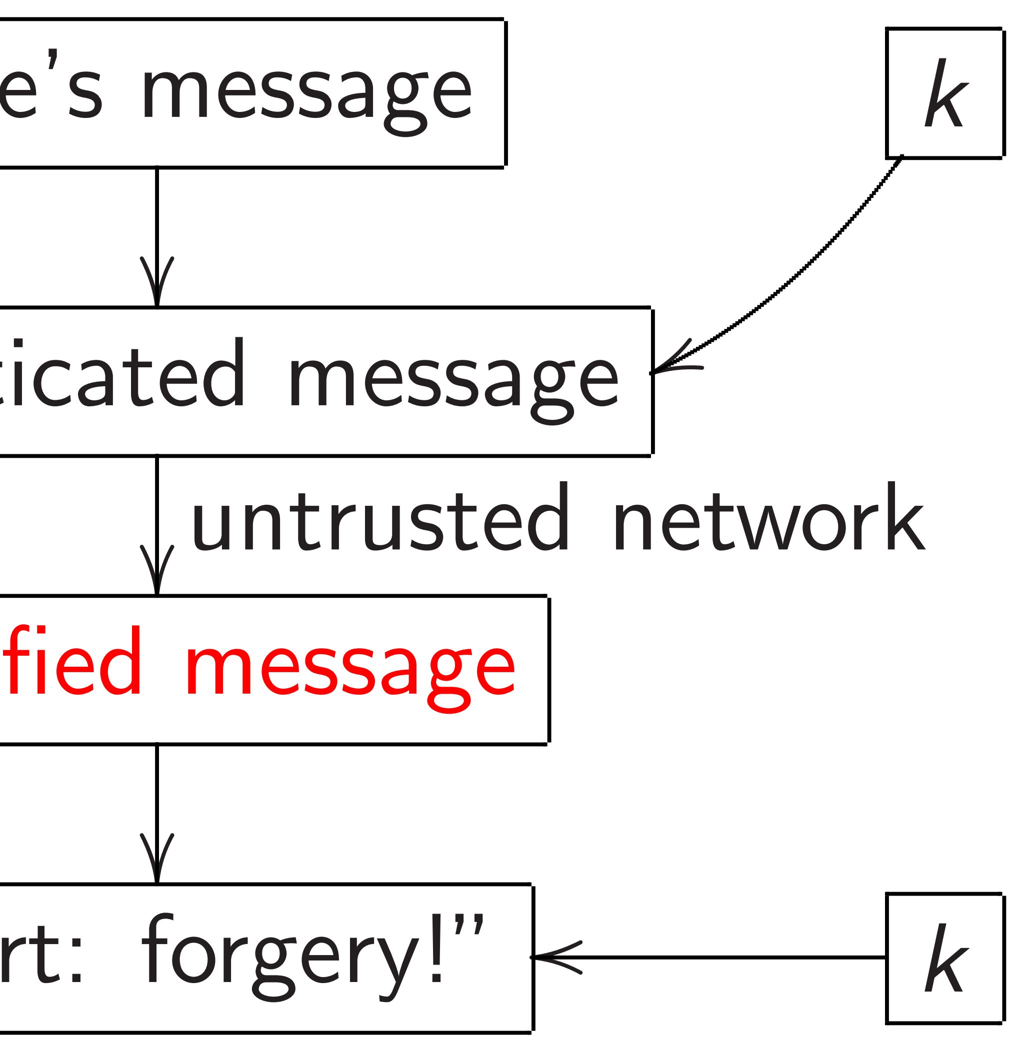

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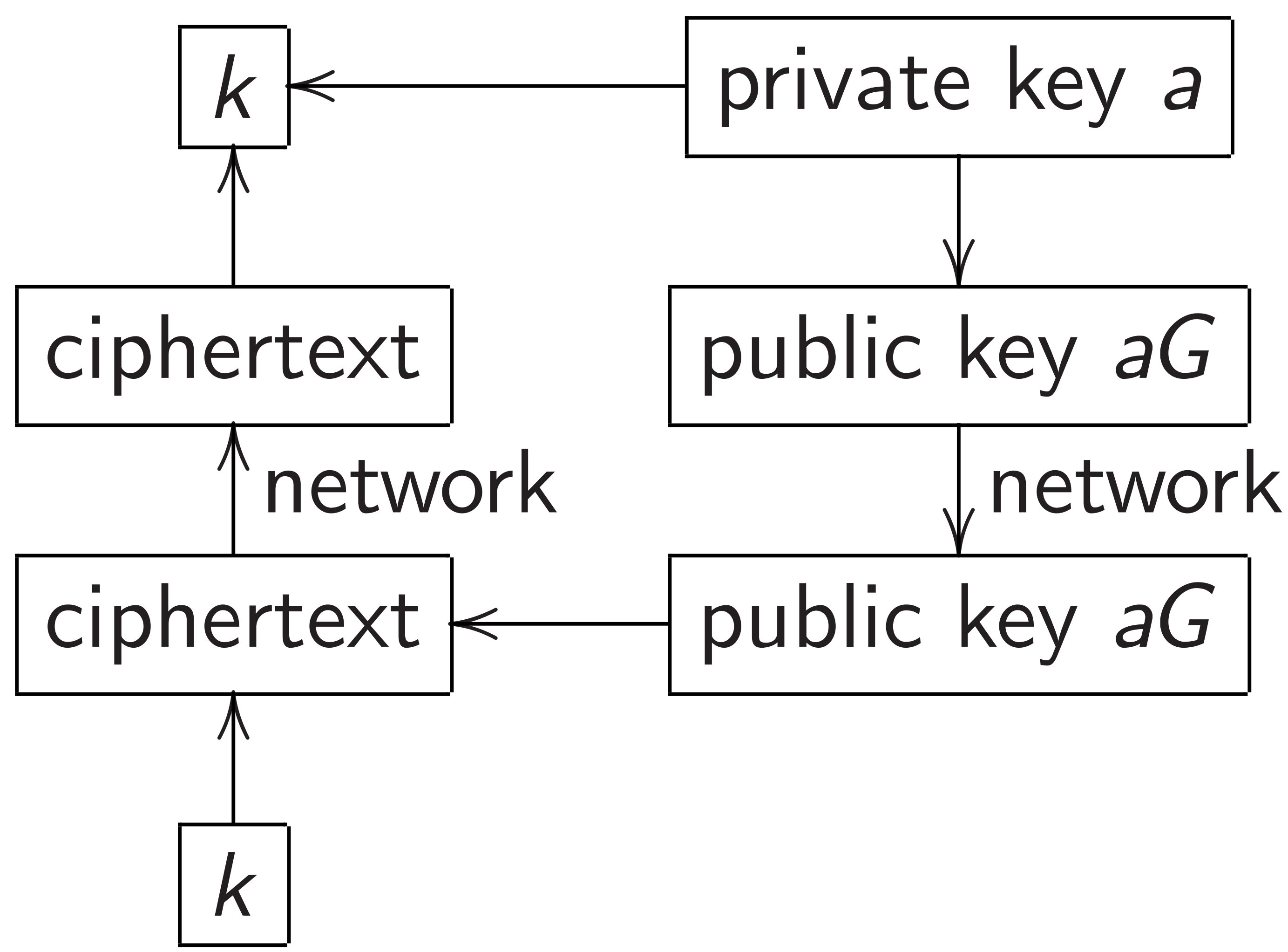

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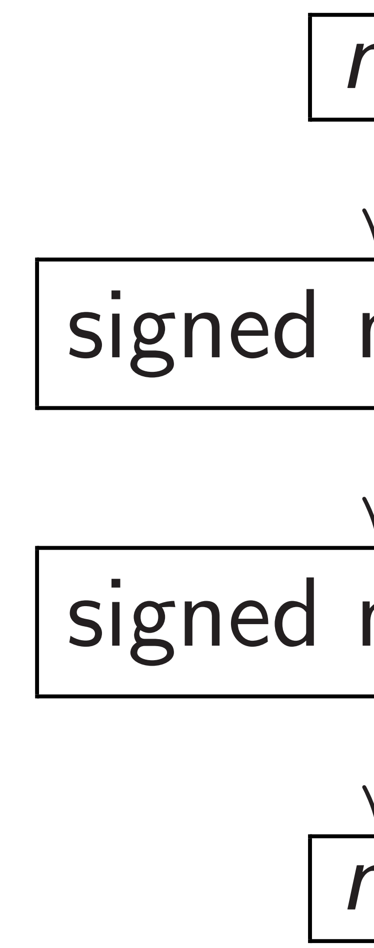

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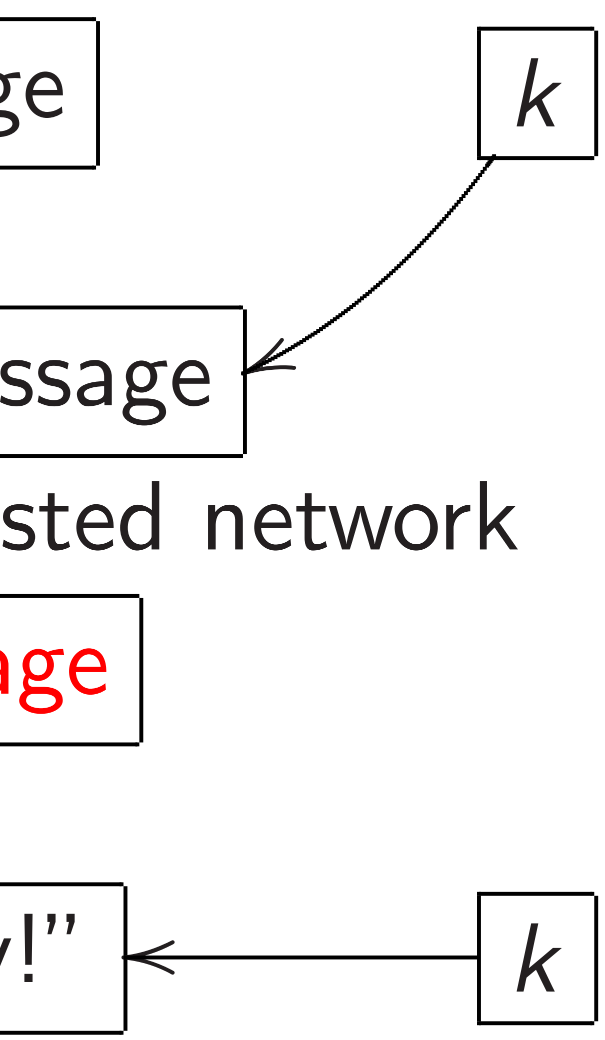

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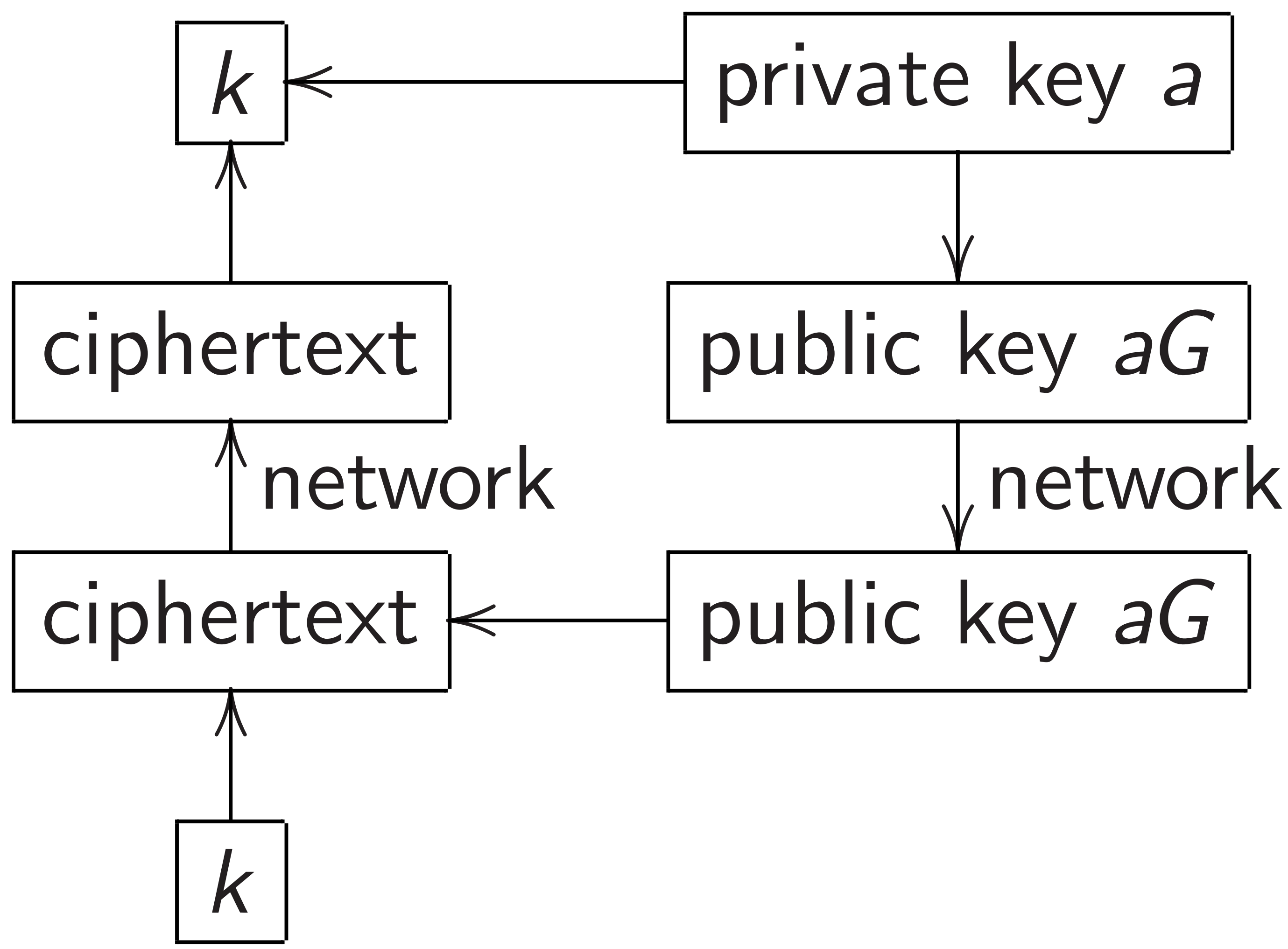

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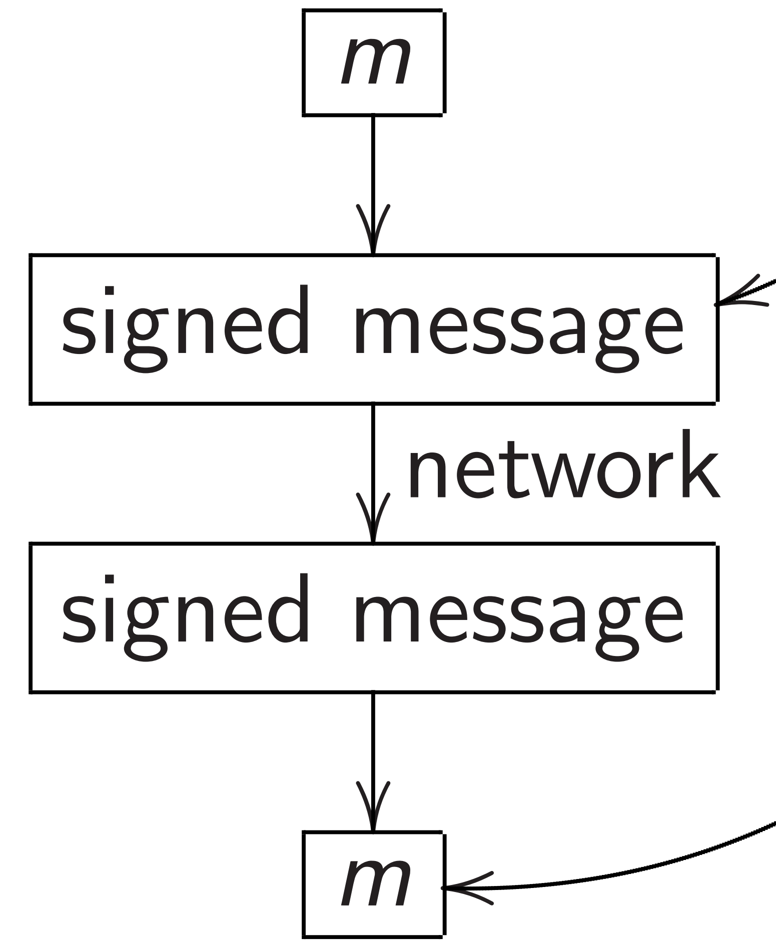

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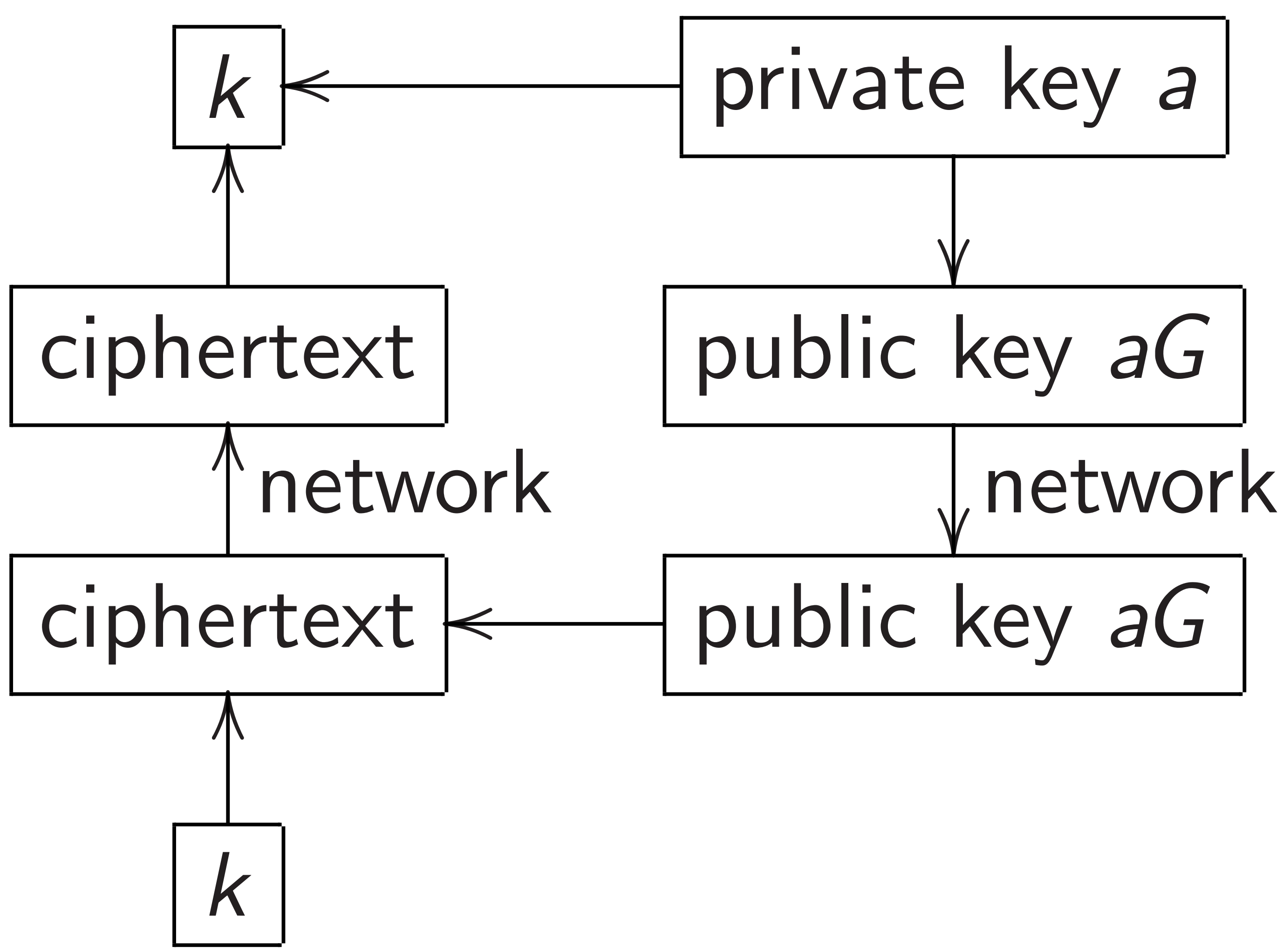

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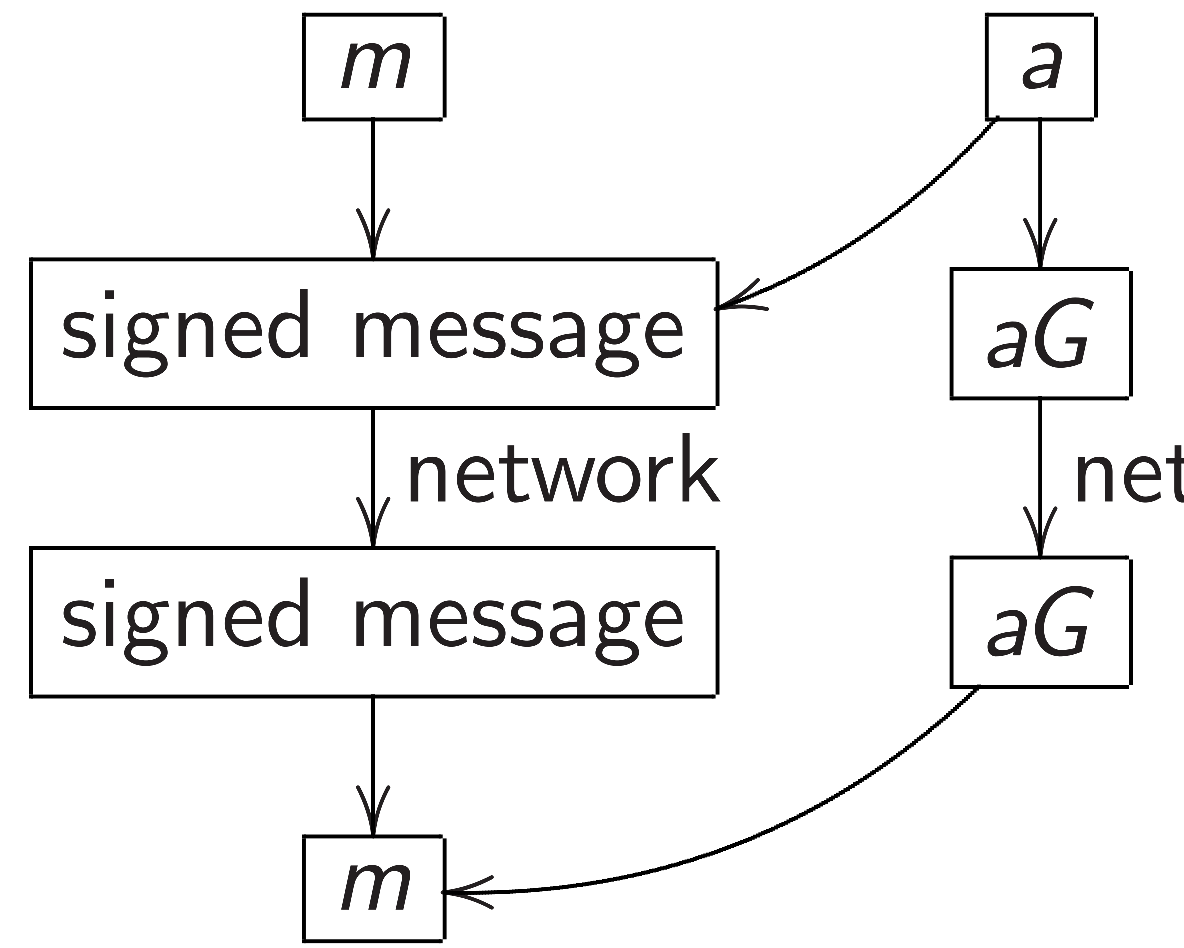

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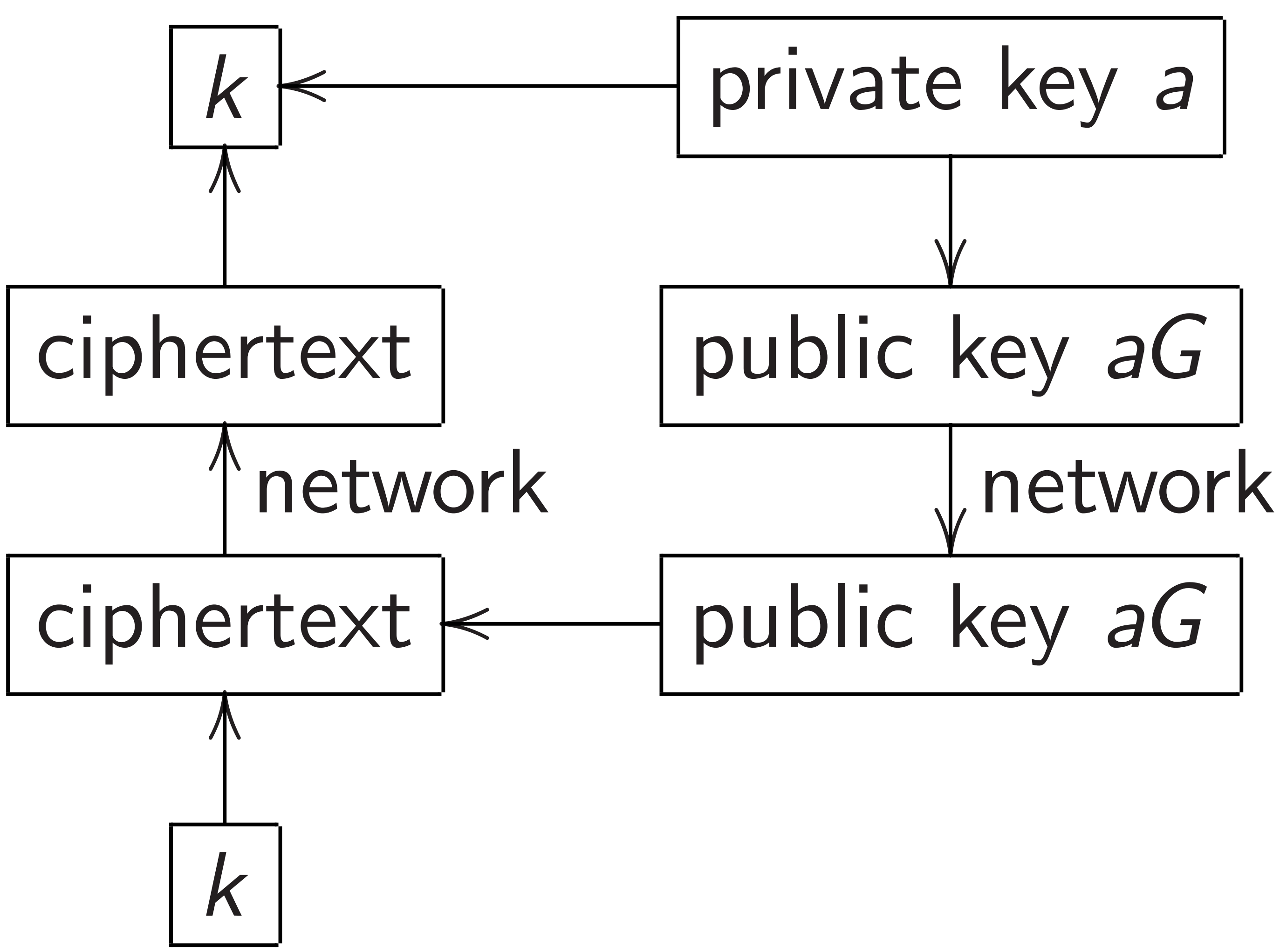

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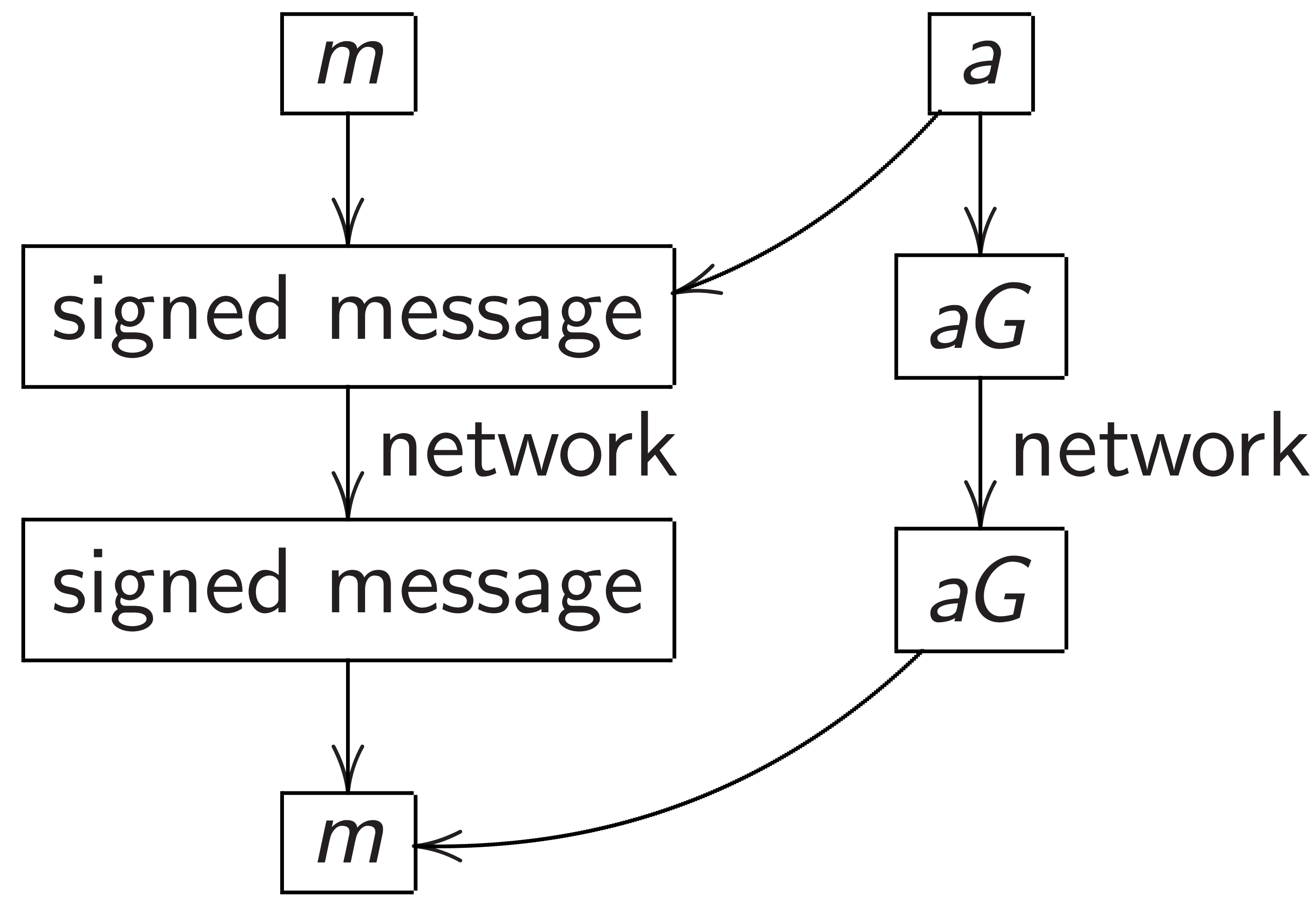

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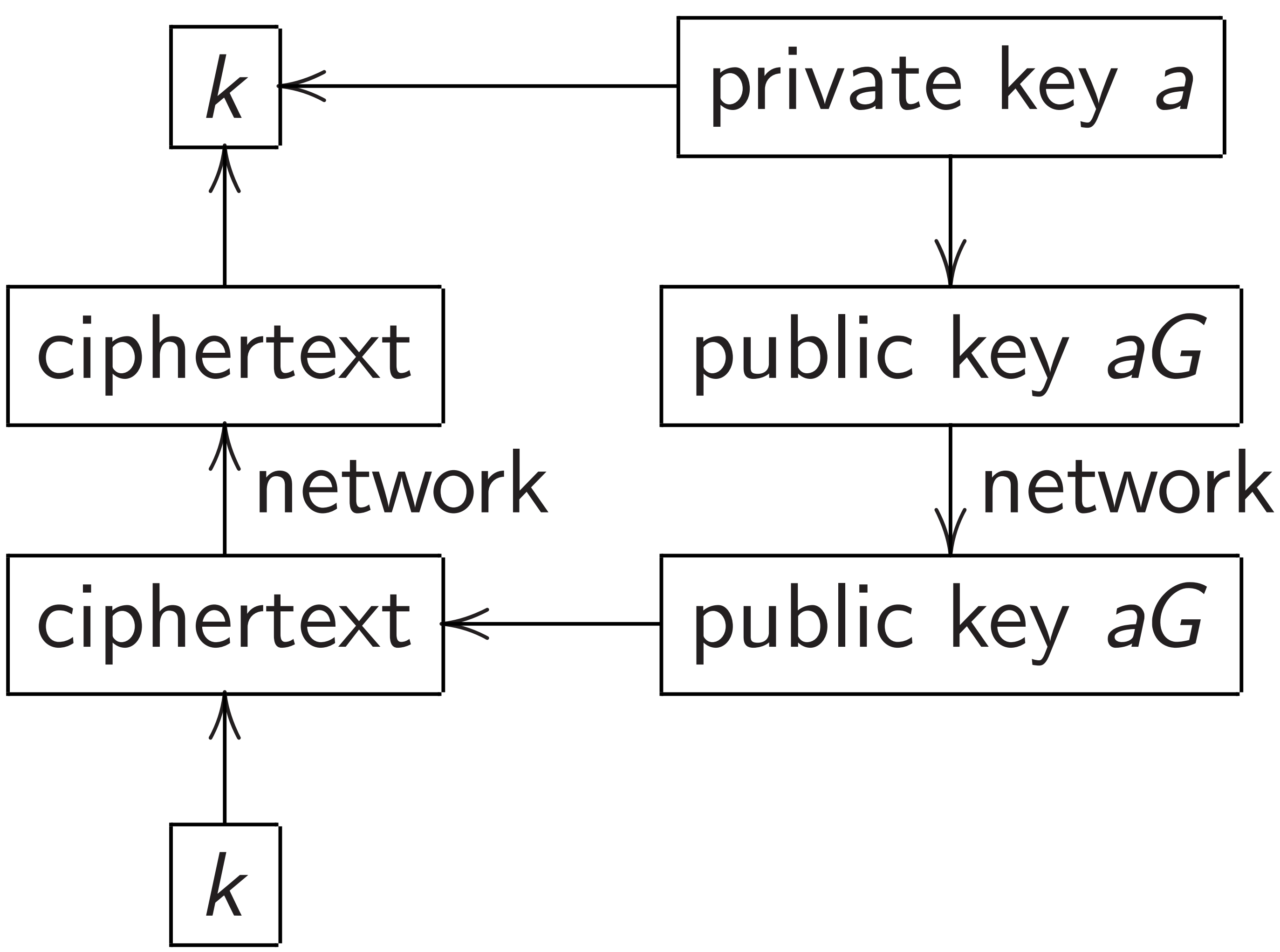

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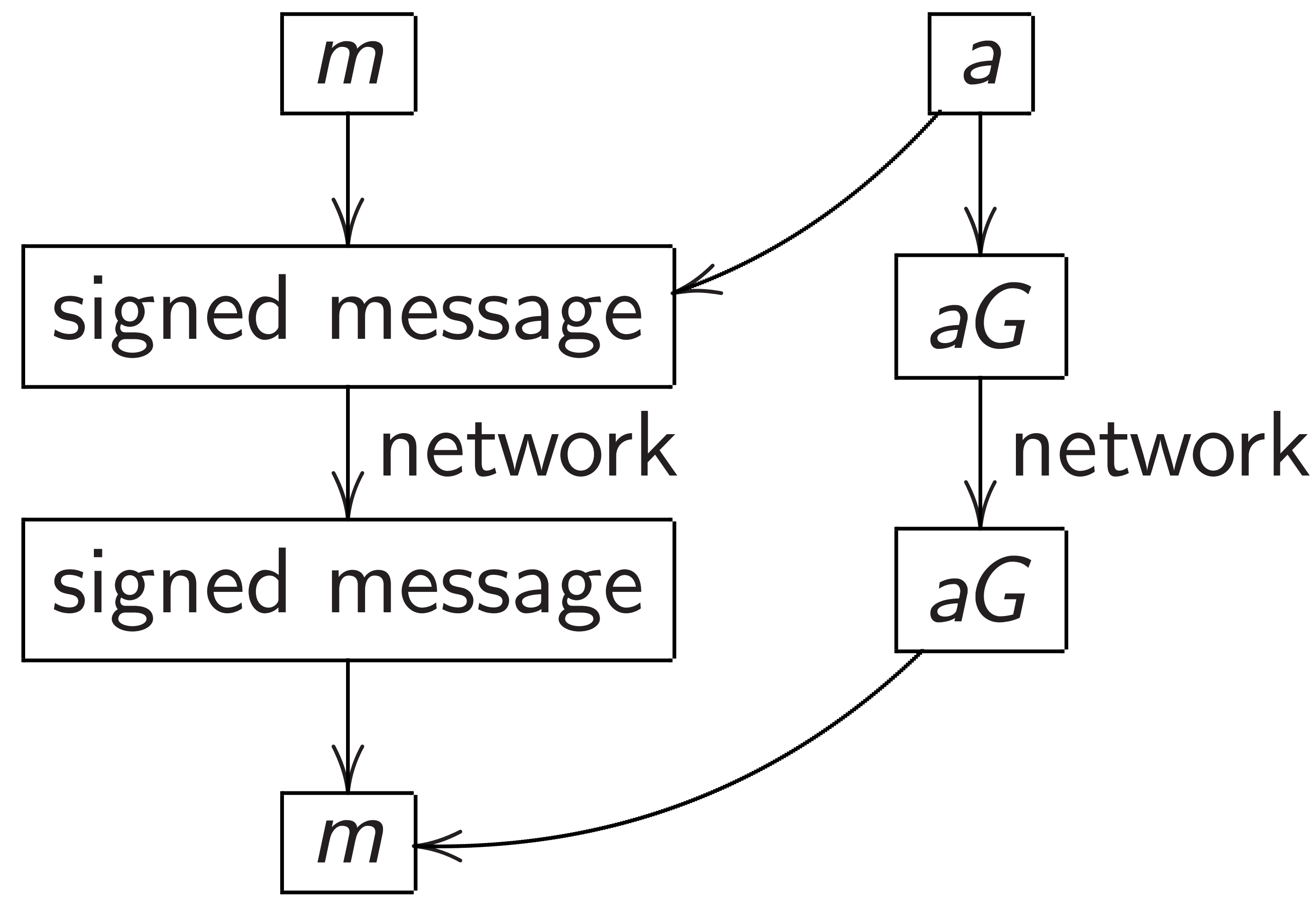

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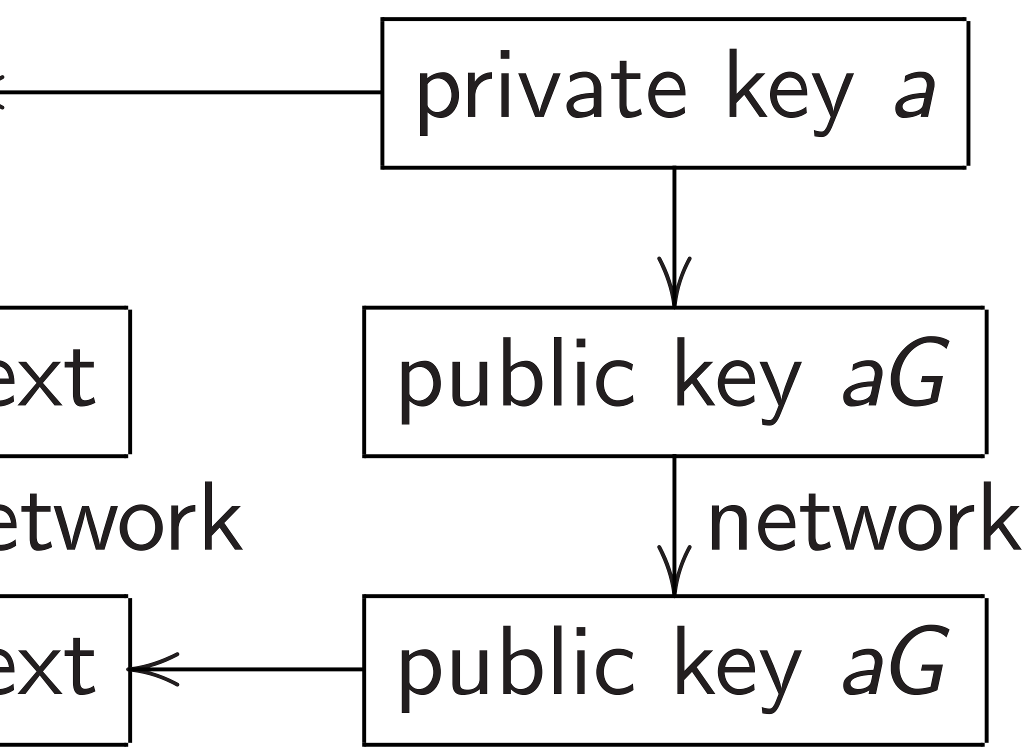

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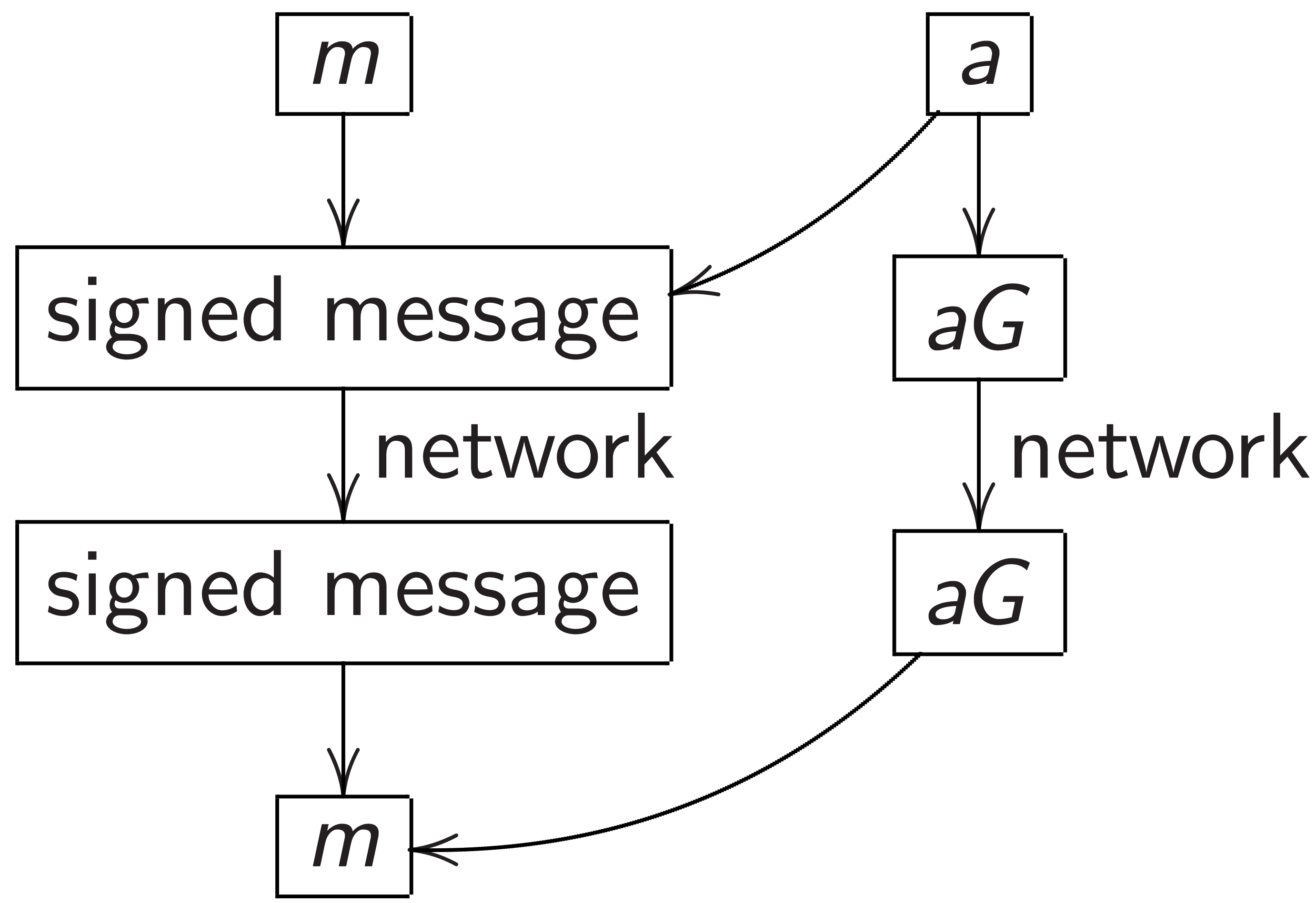

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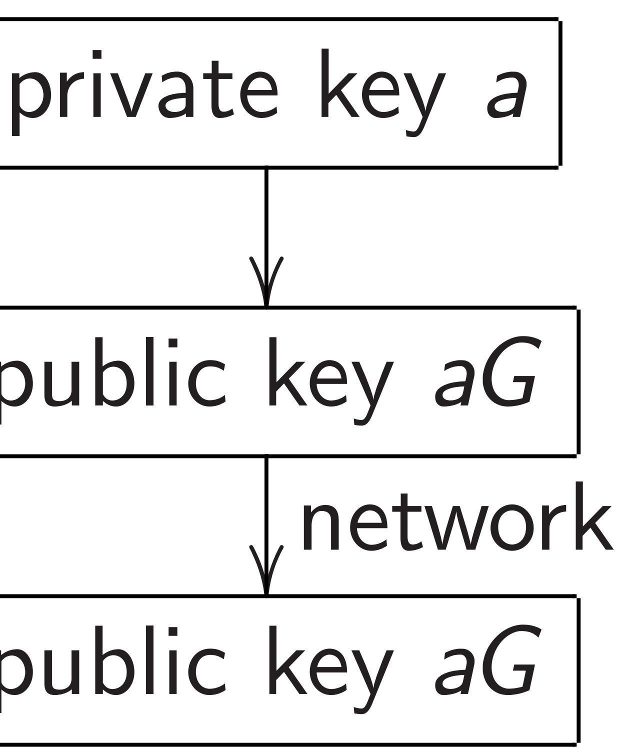

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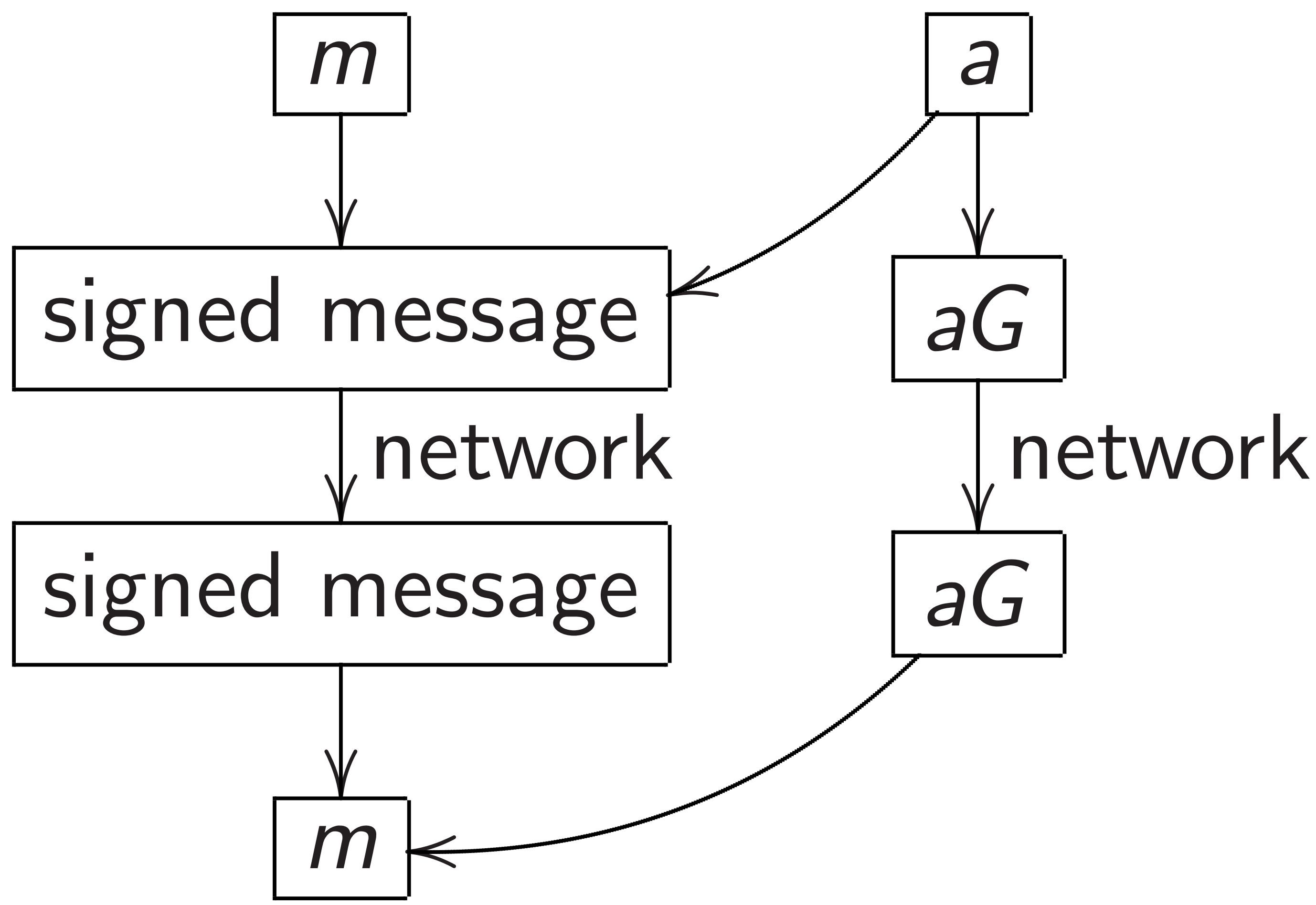

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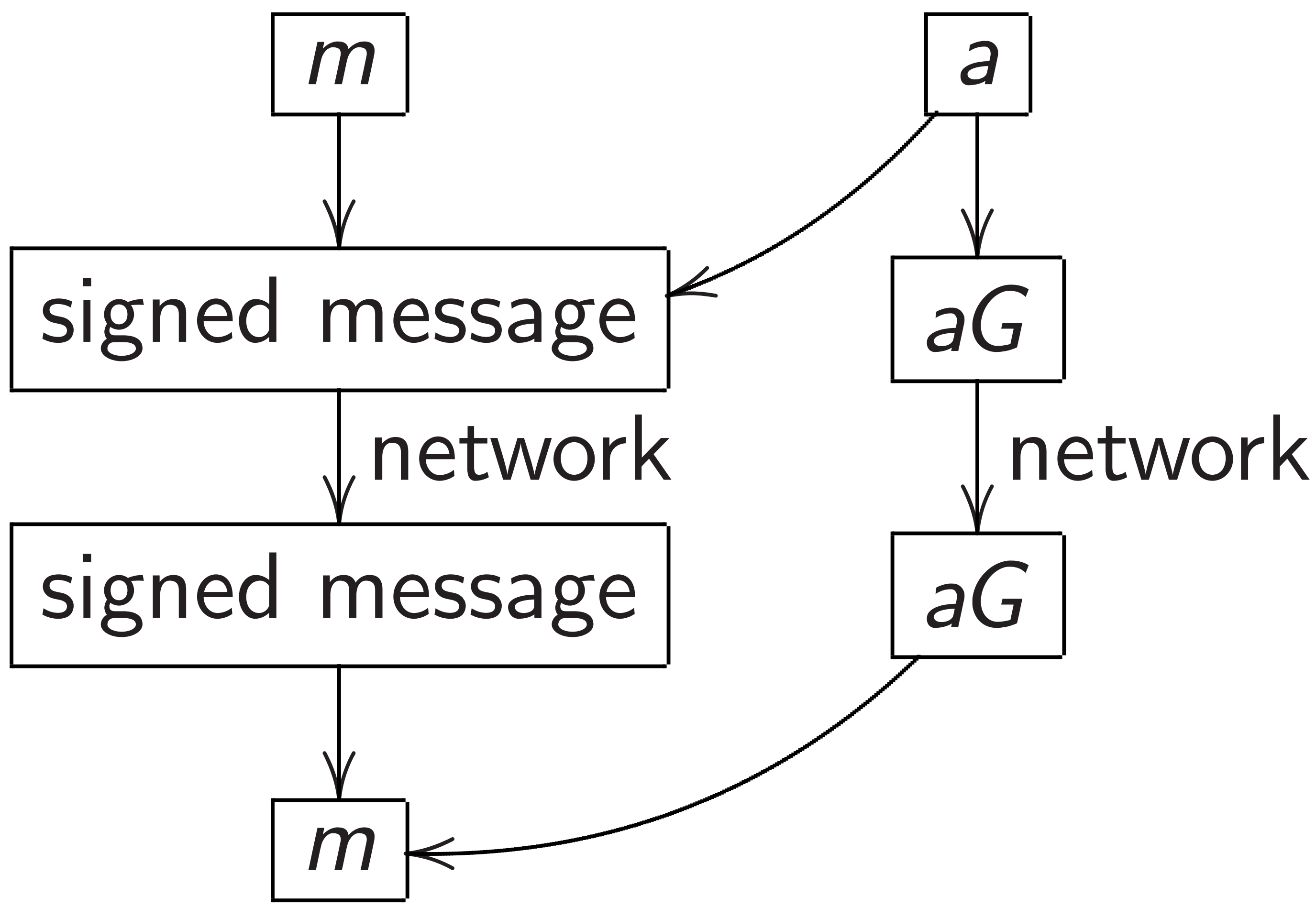

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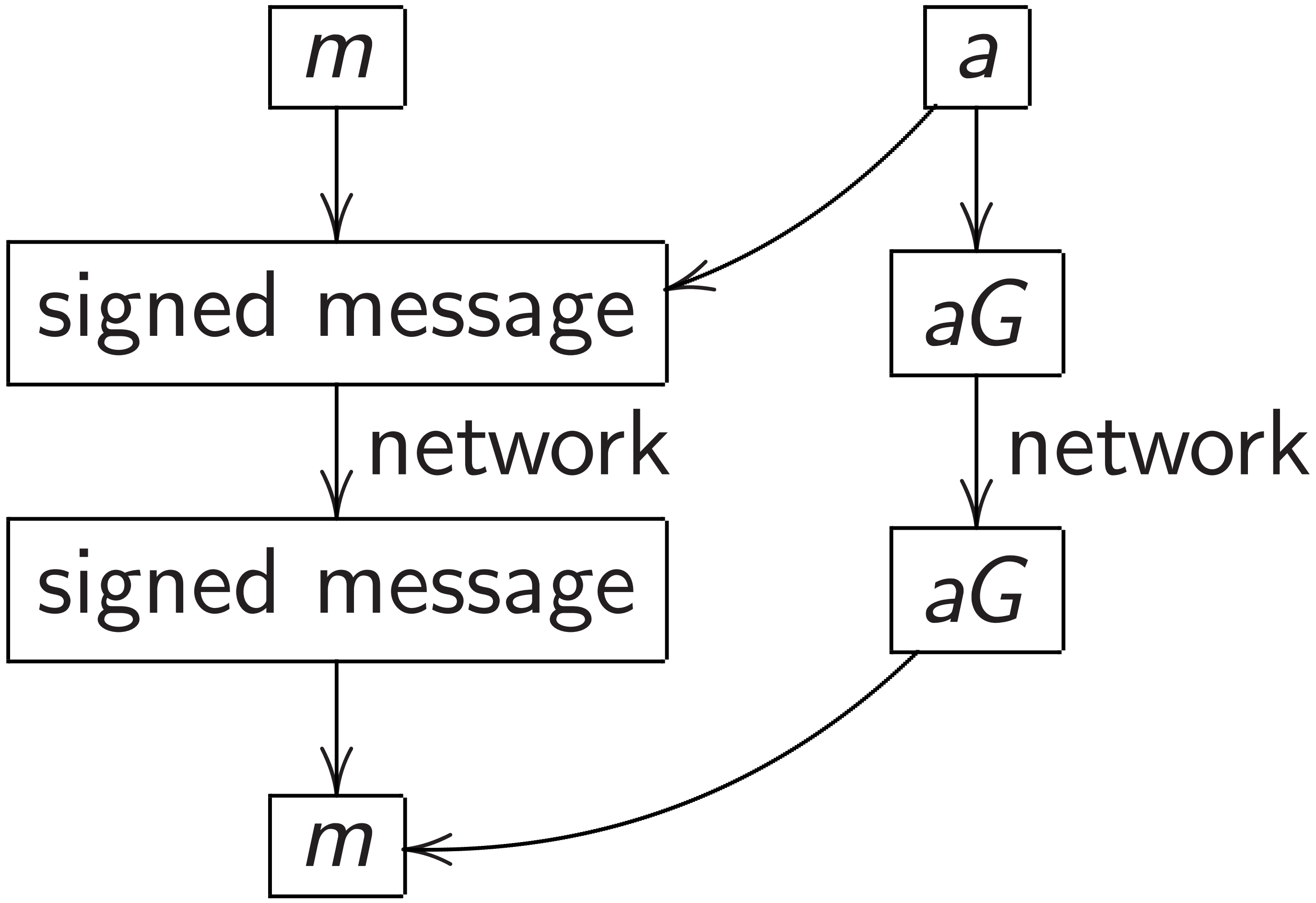

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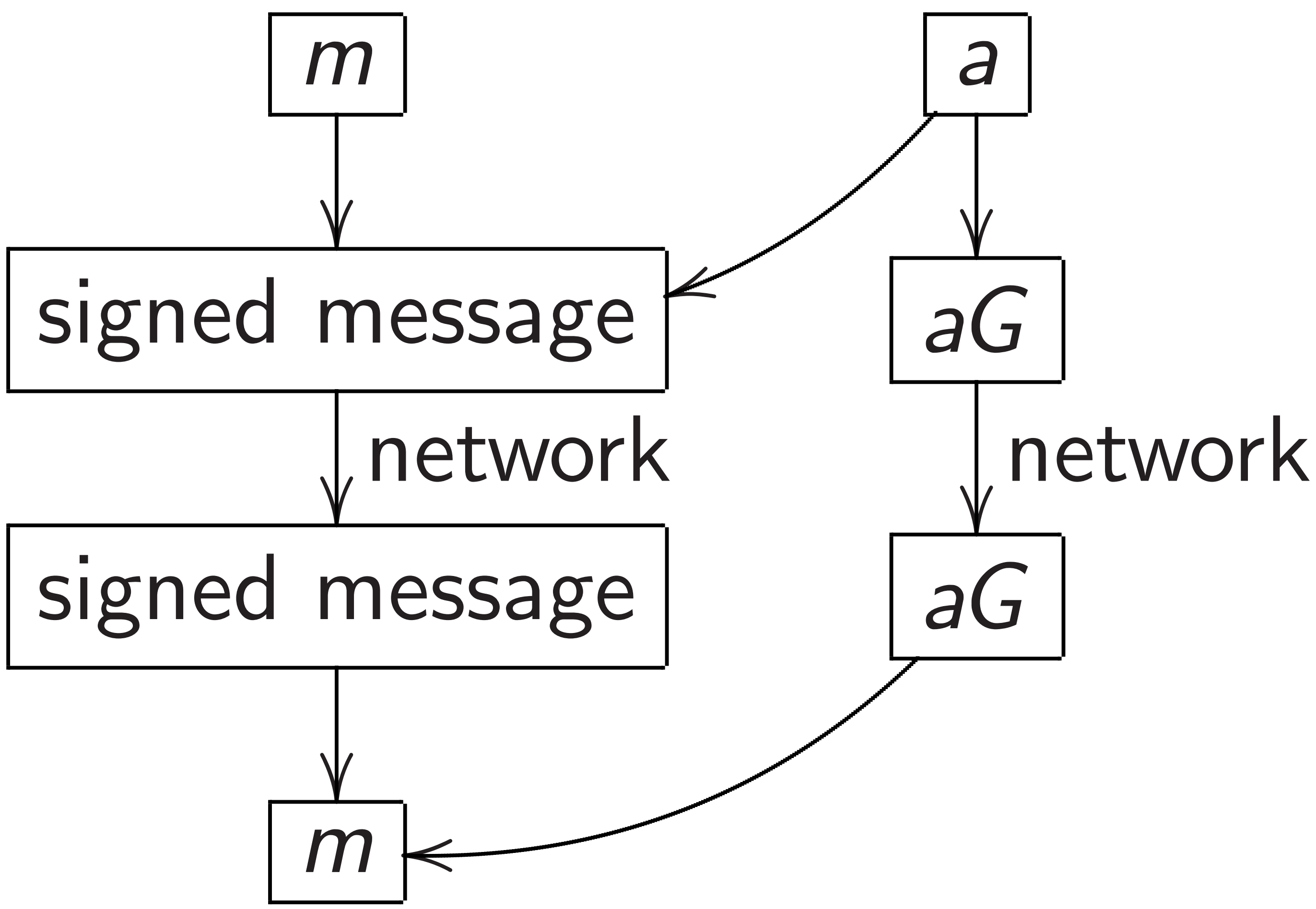

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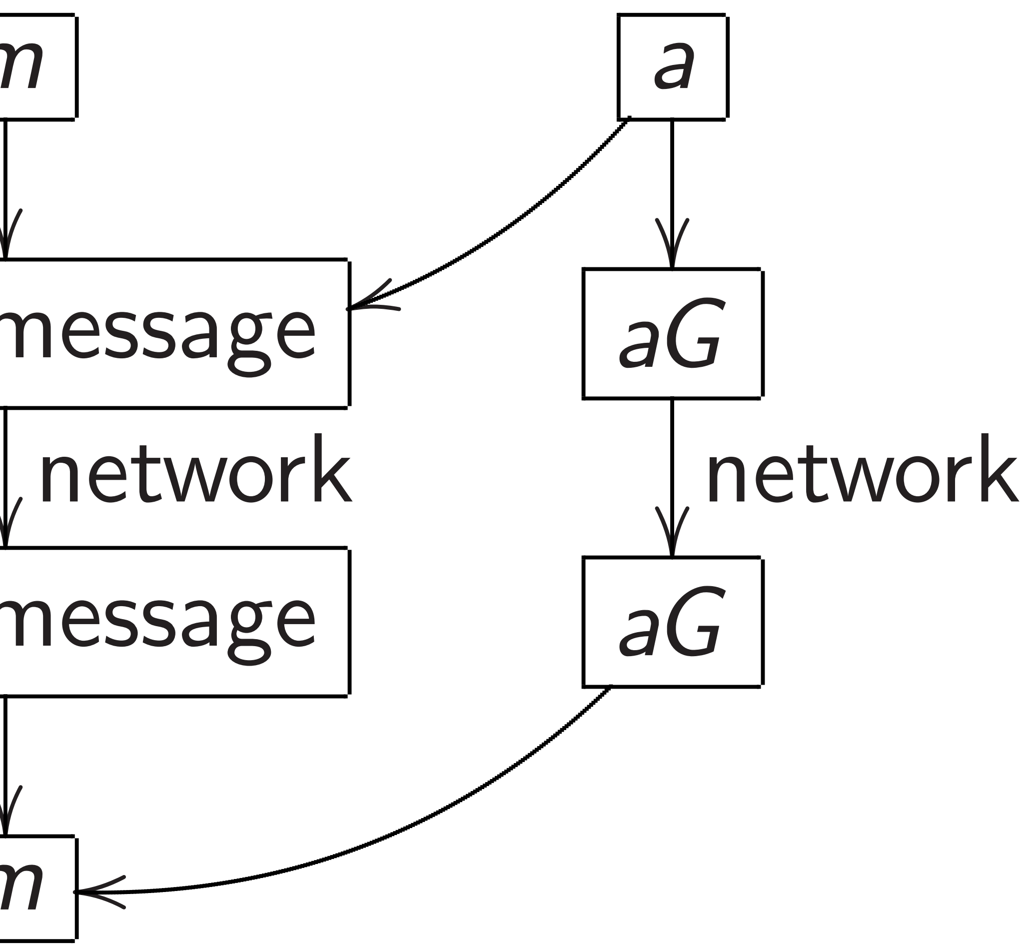

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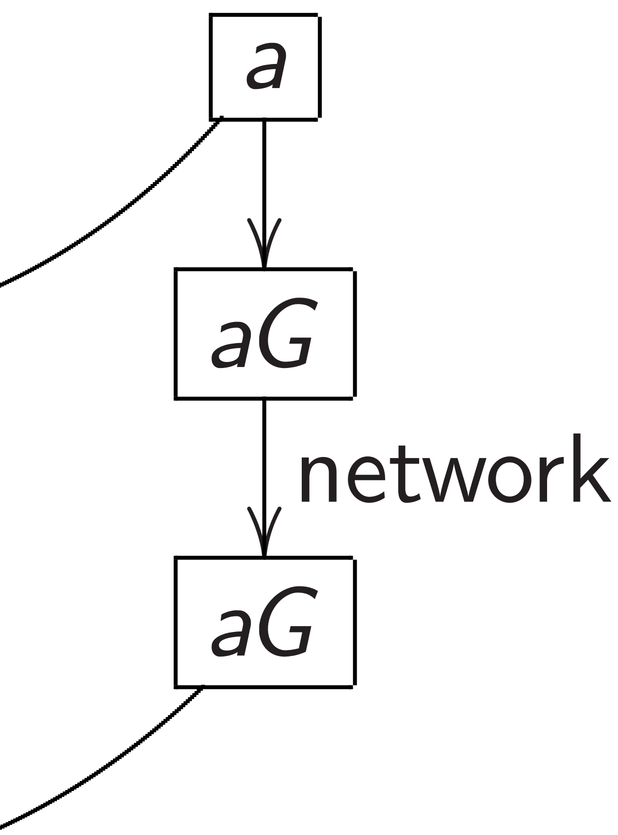

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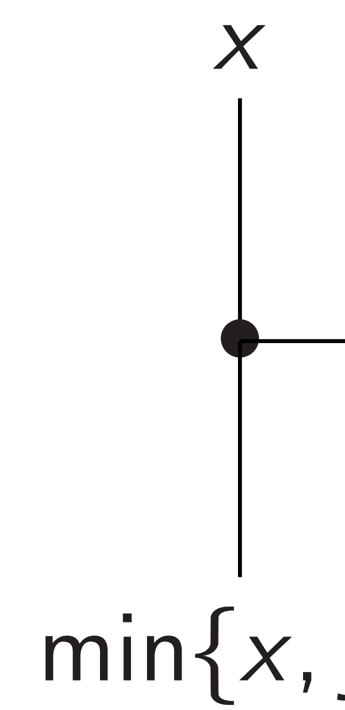

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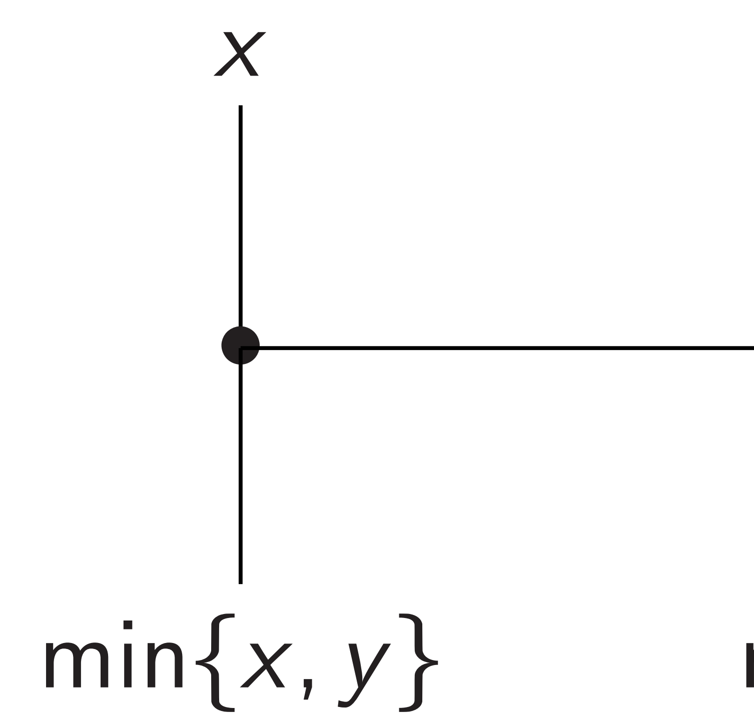

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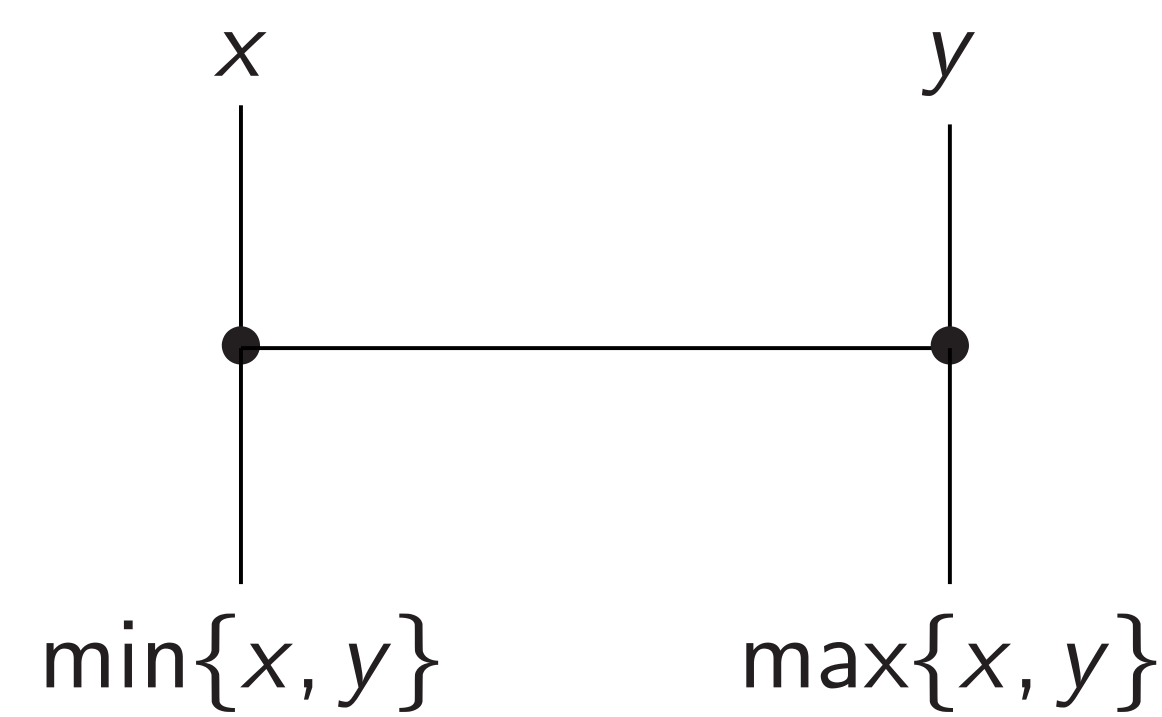

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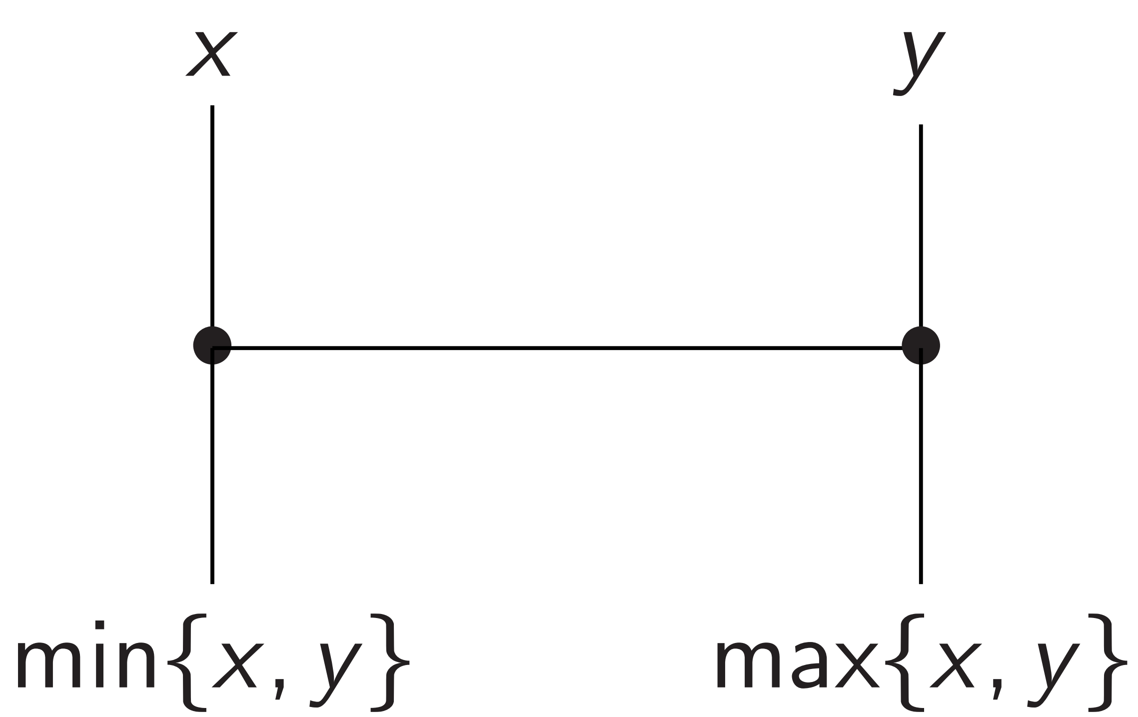

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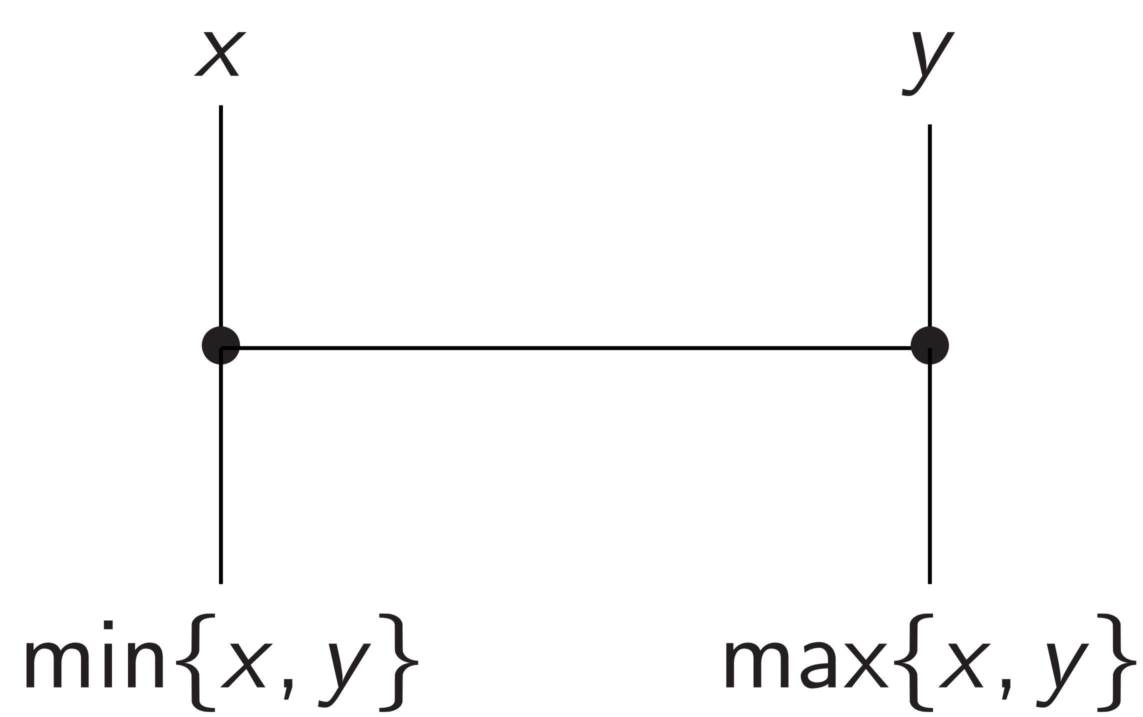

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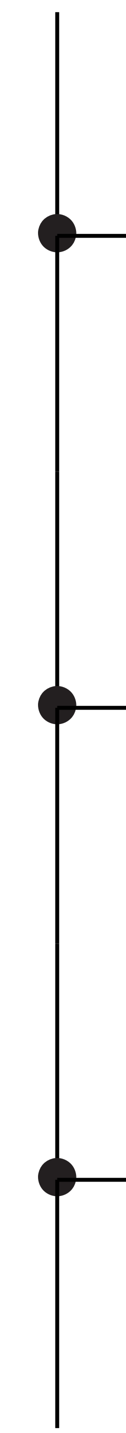

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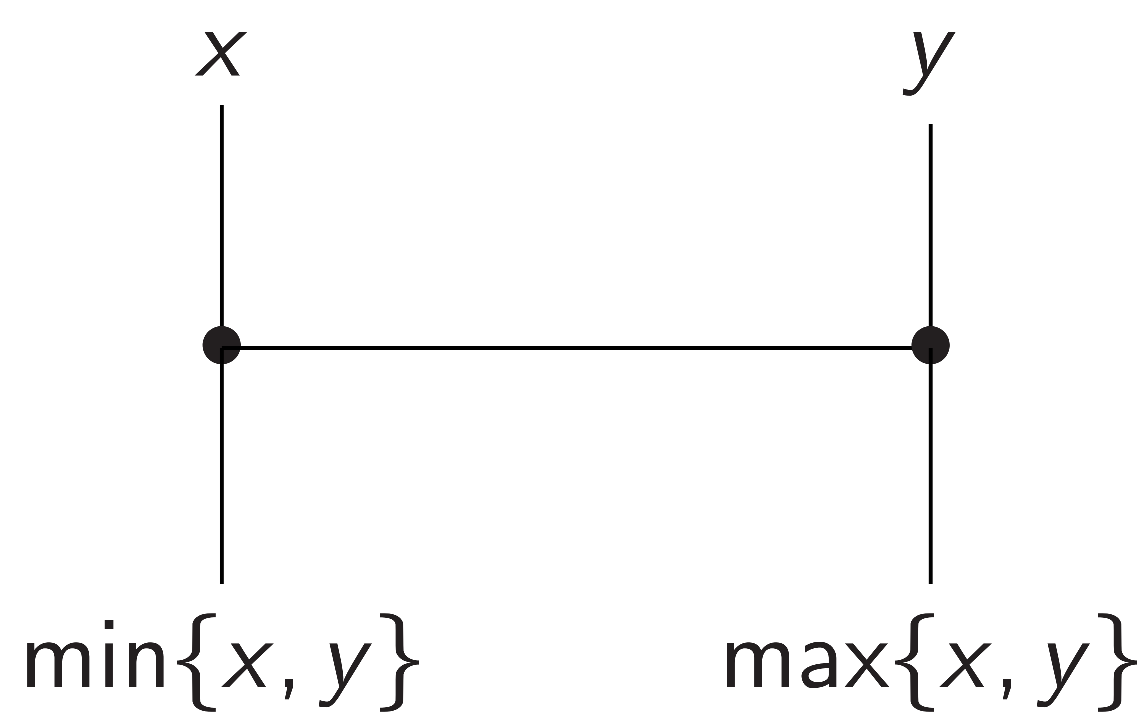

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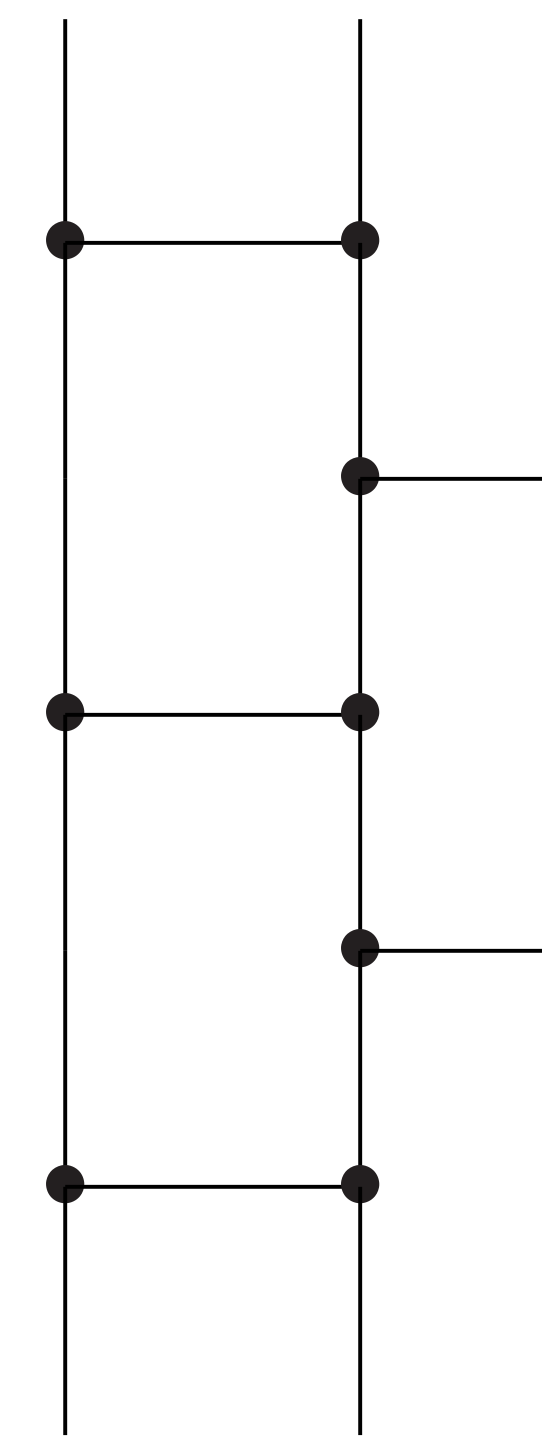

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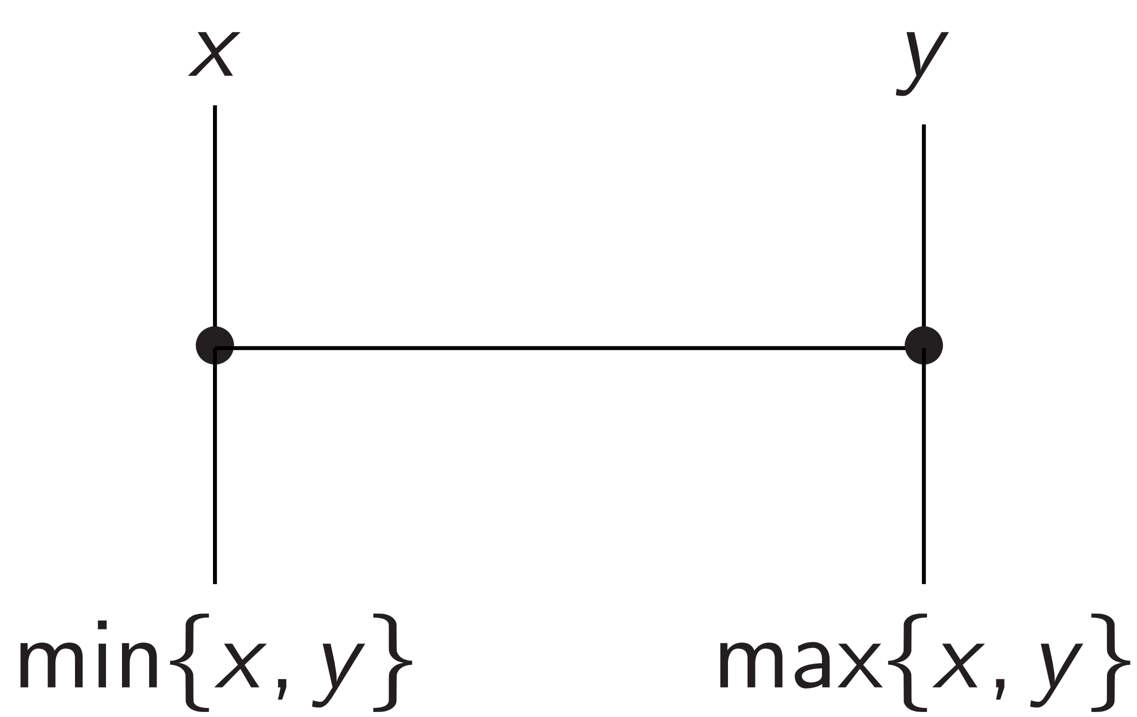

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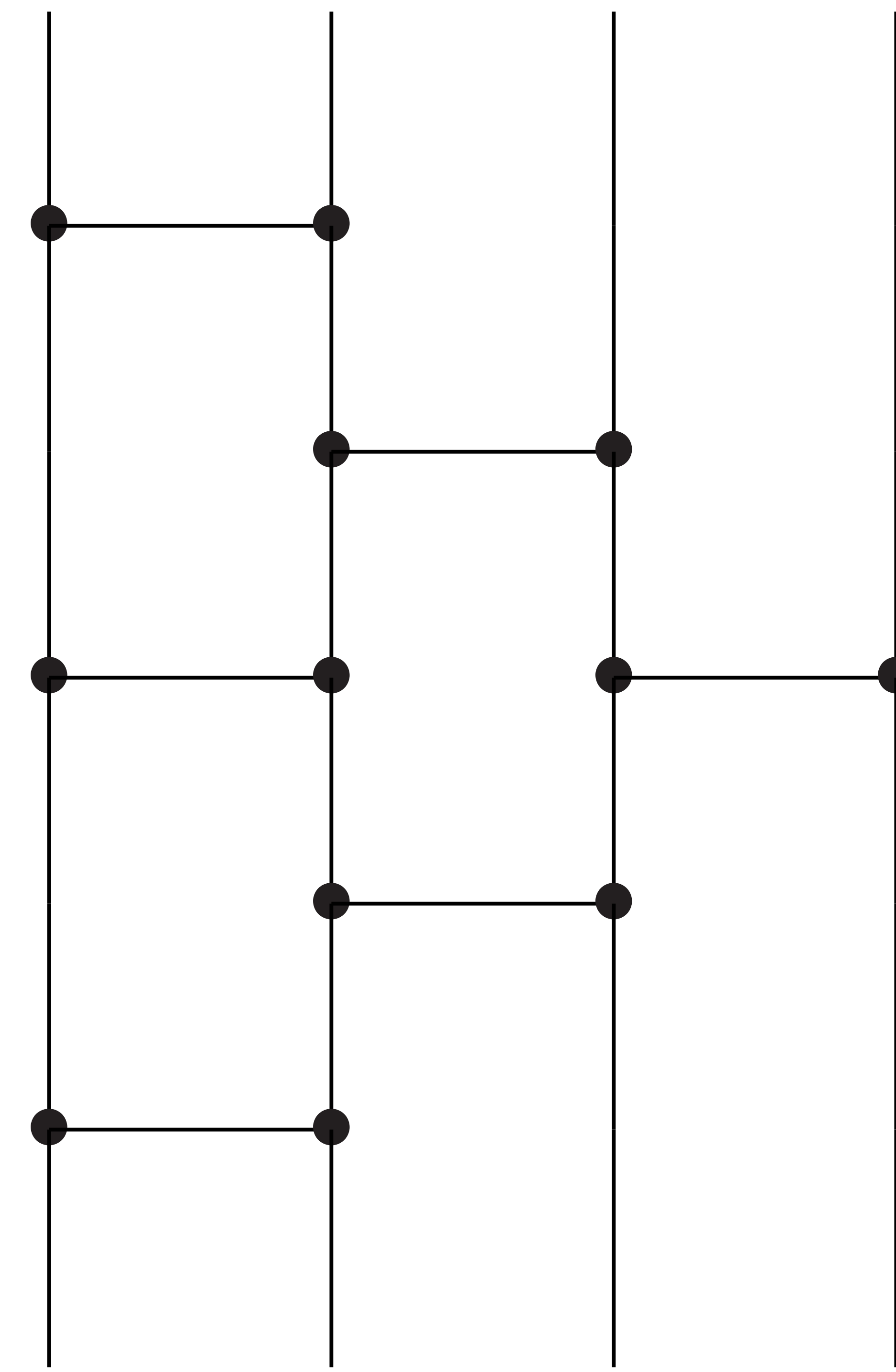

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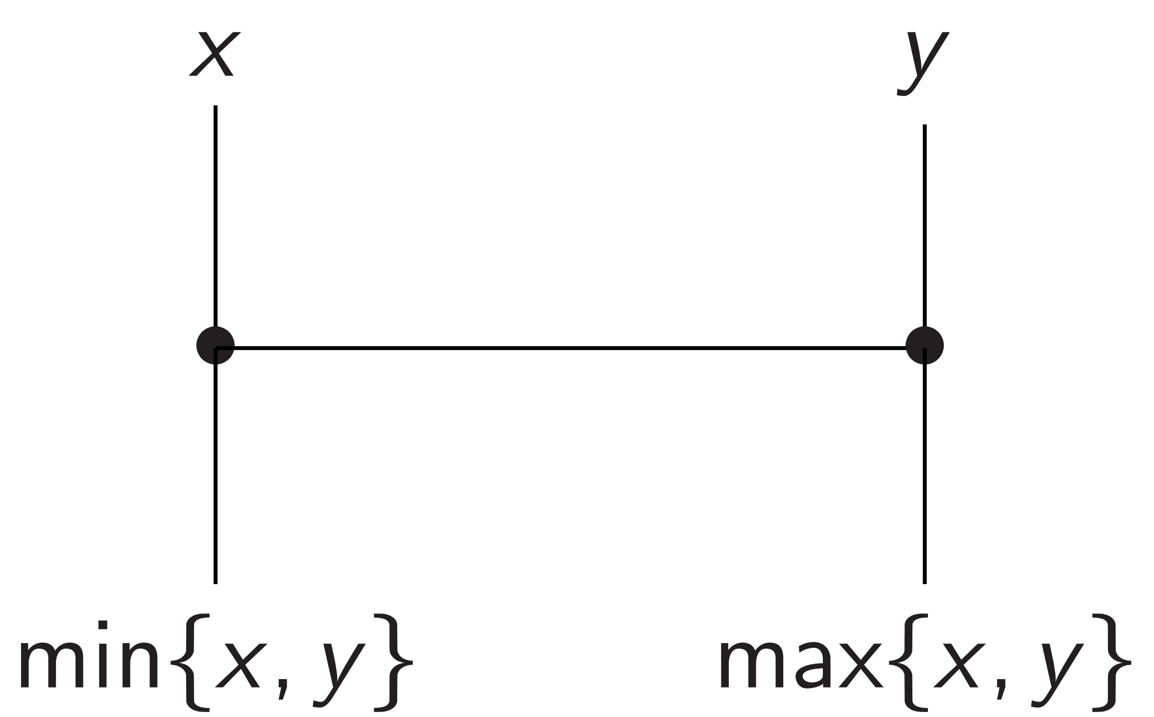

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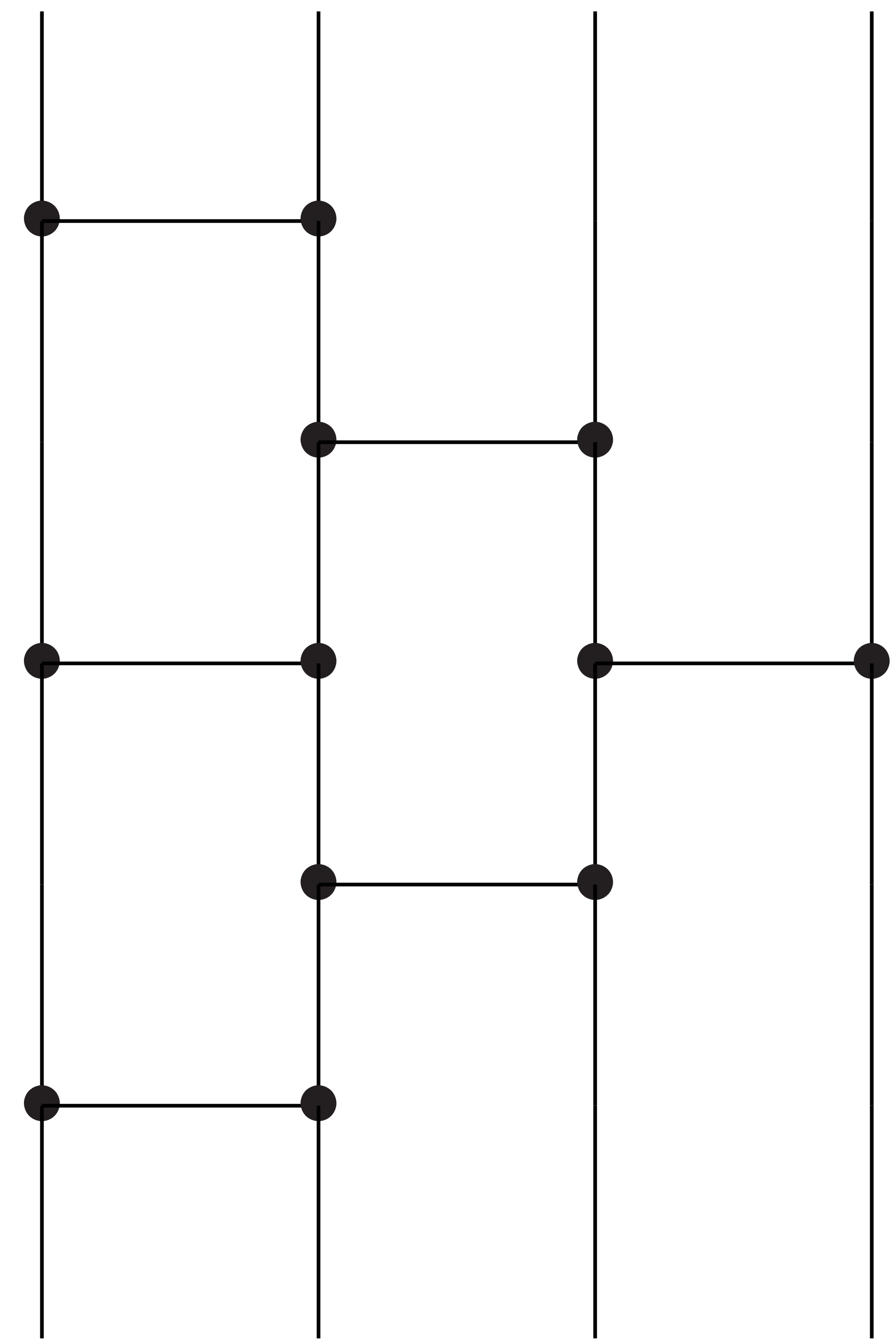

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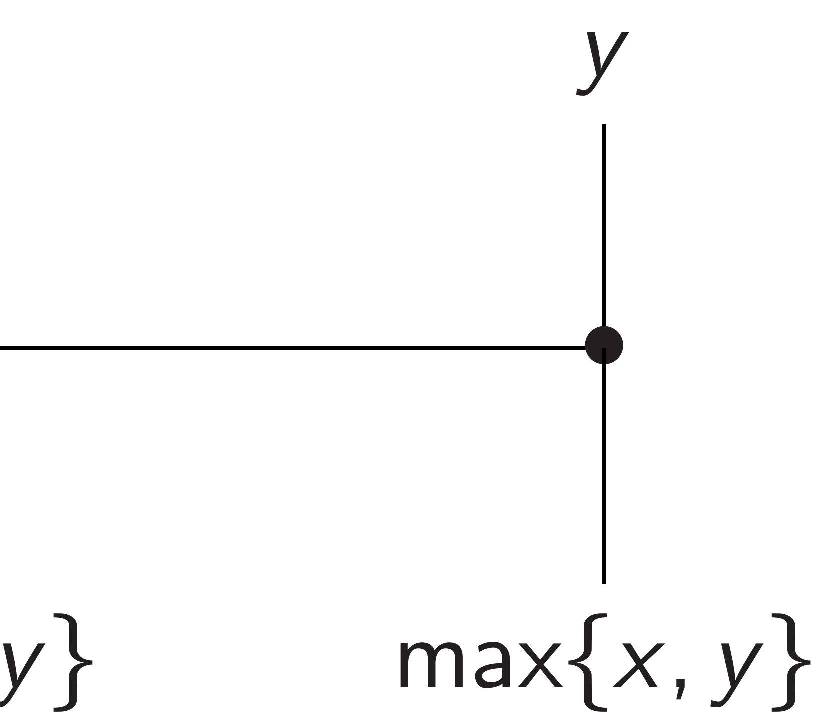

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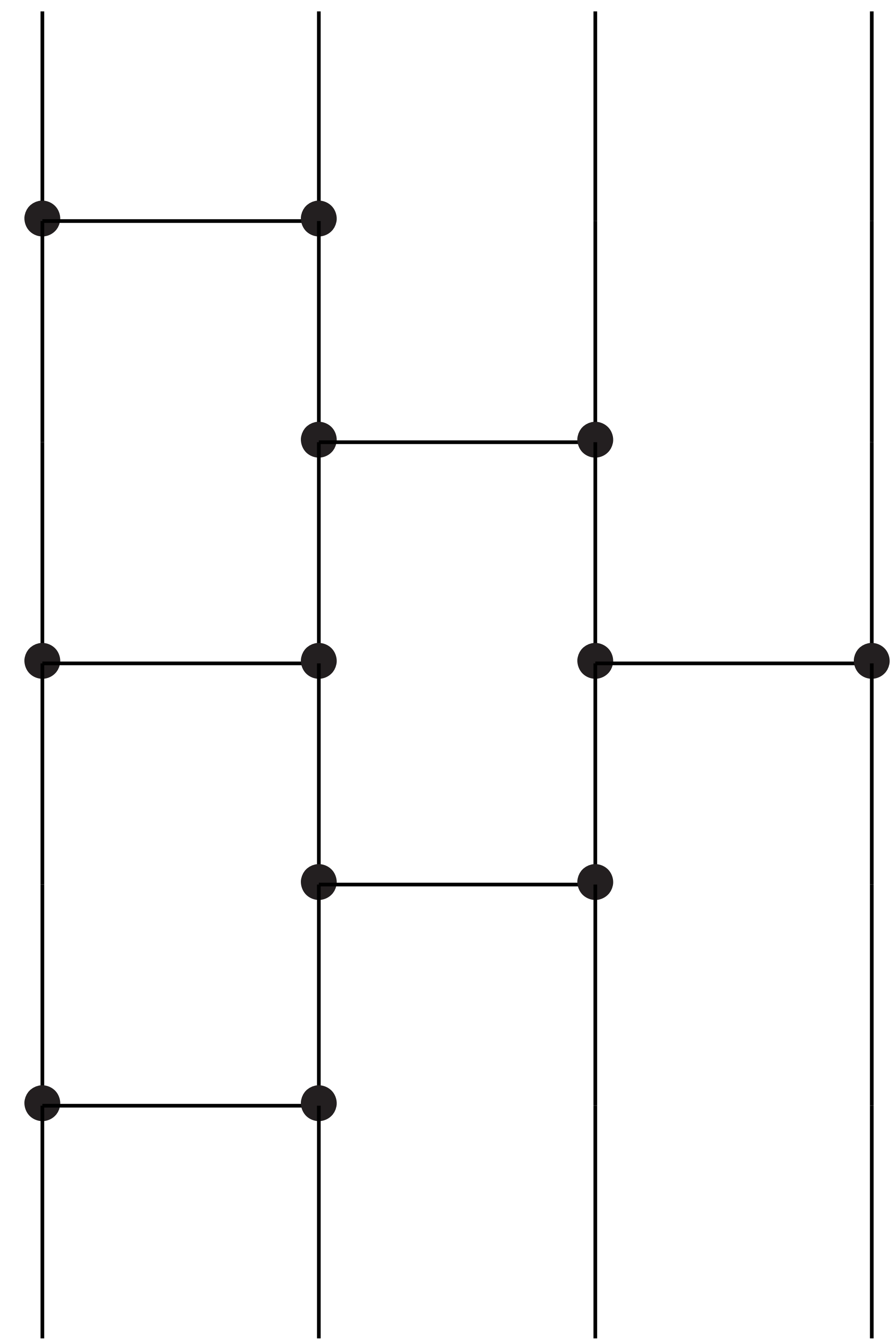
Combine comparators into a **sorting network** for more inputs.

Example of a sorting network:



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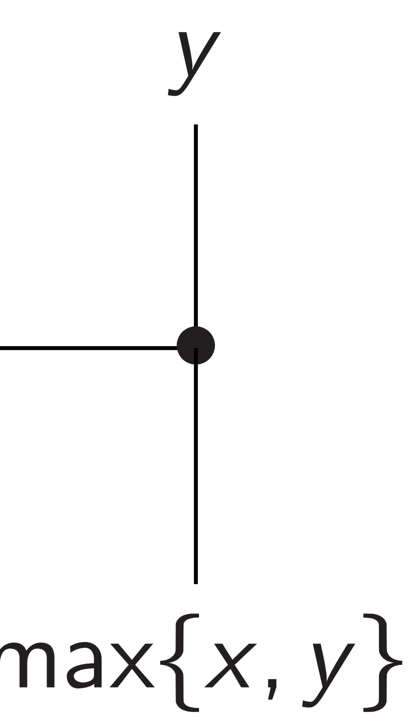

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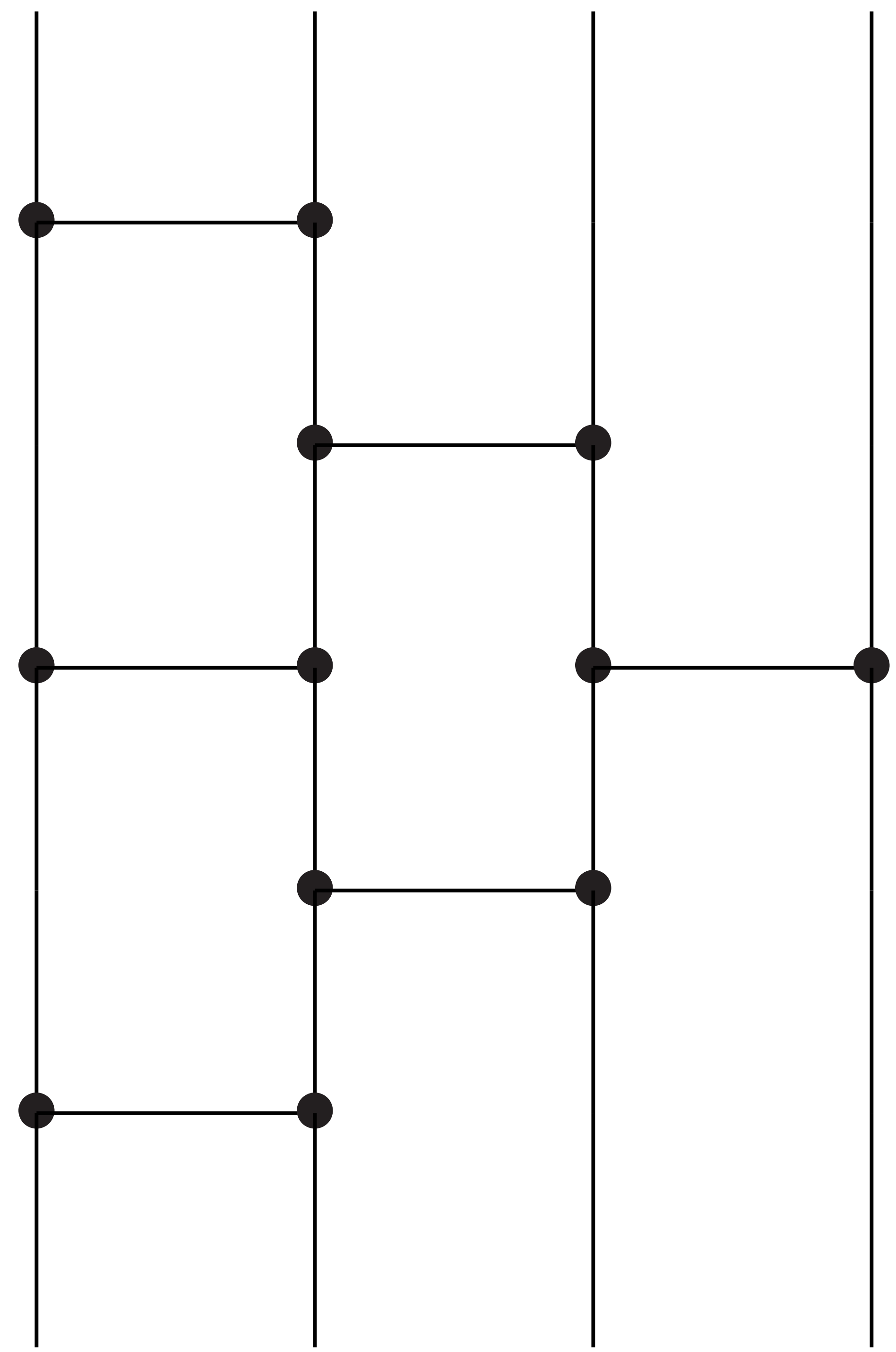

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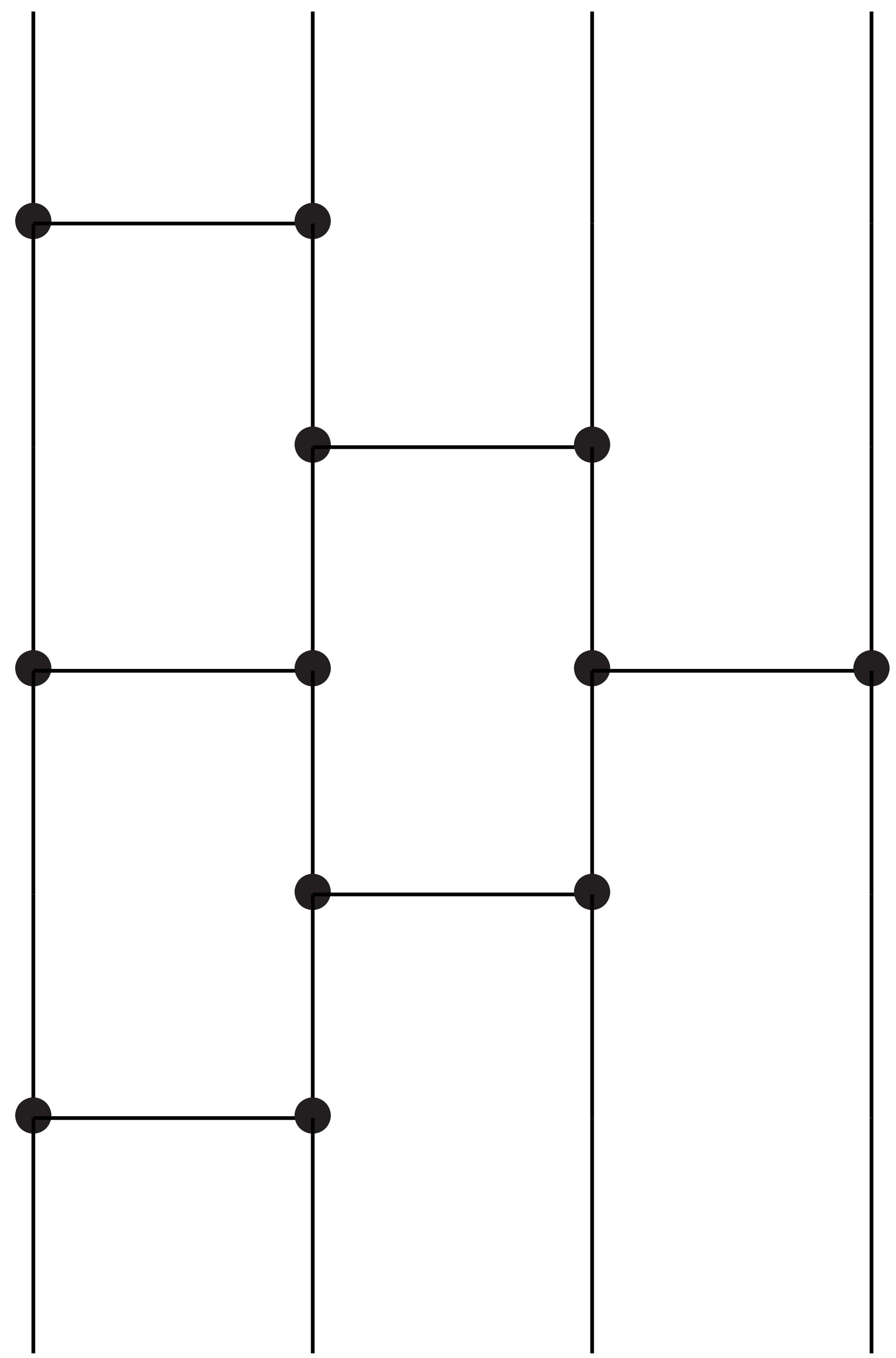

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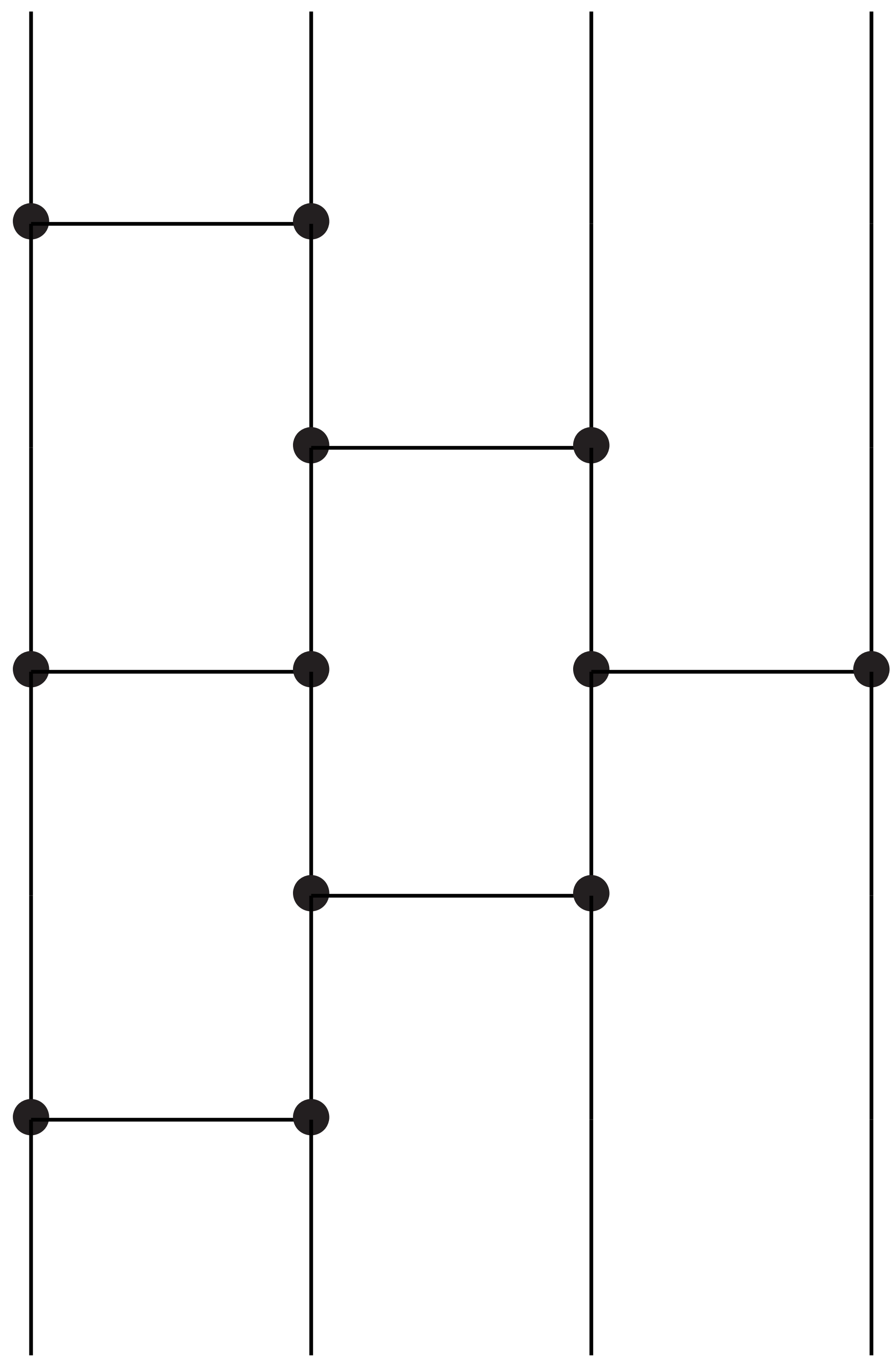

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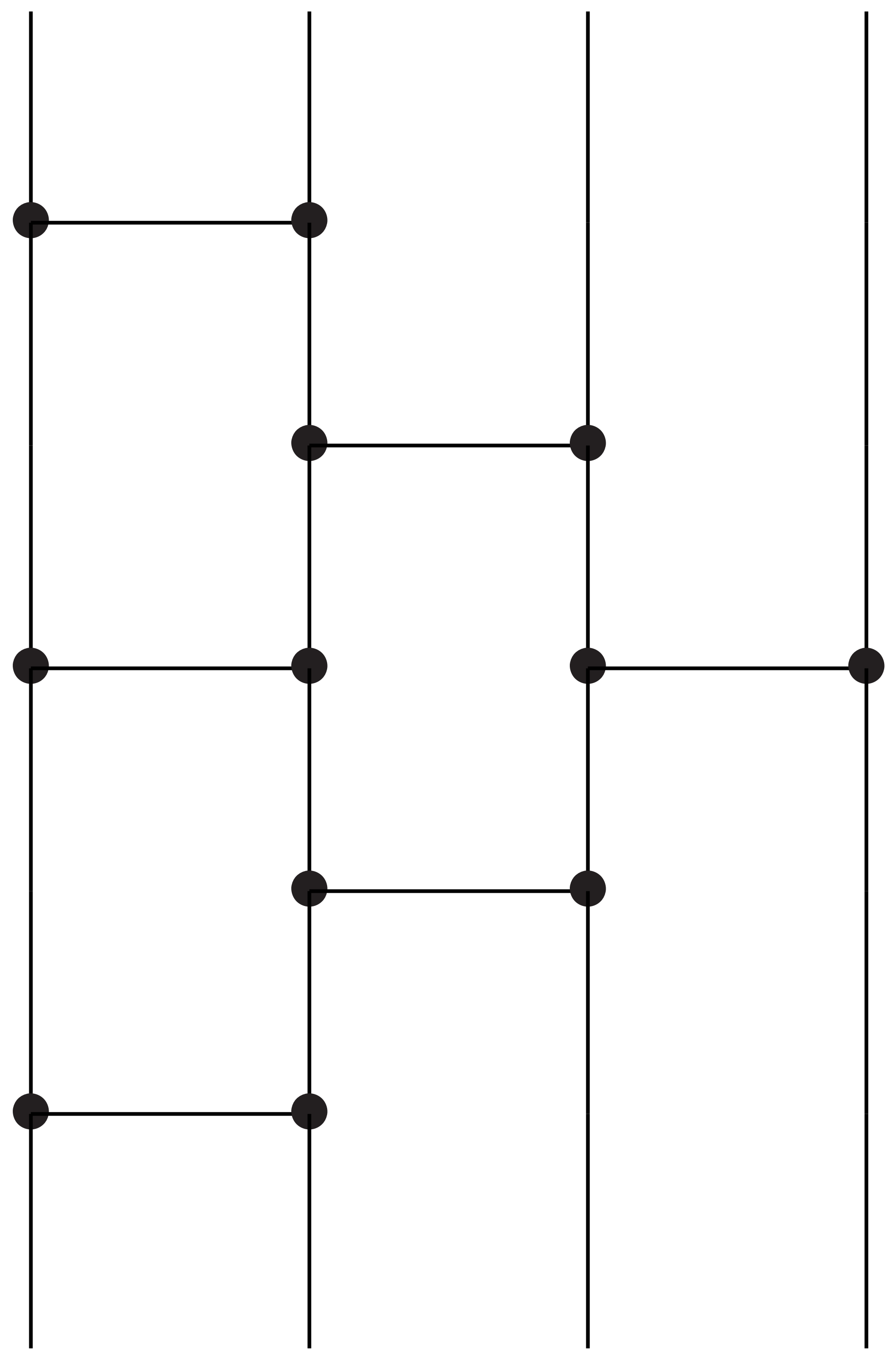

Positions of comparators in a sorting network are independent of the input. Naturally constant-time.

But $(n^2 - n)/2$ comparators produce complaints about performance as n increases.

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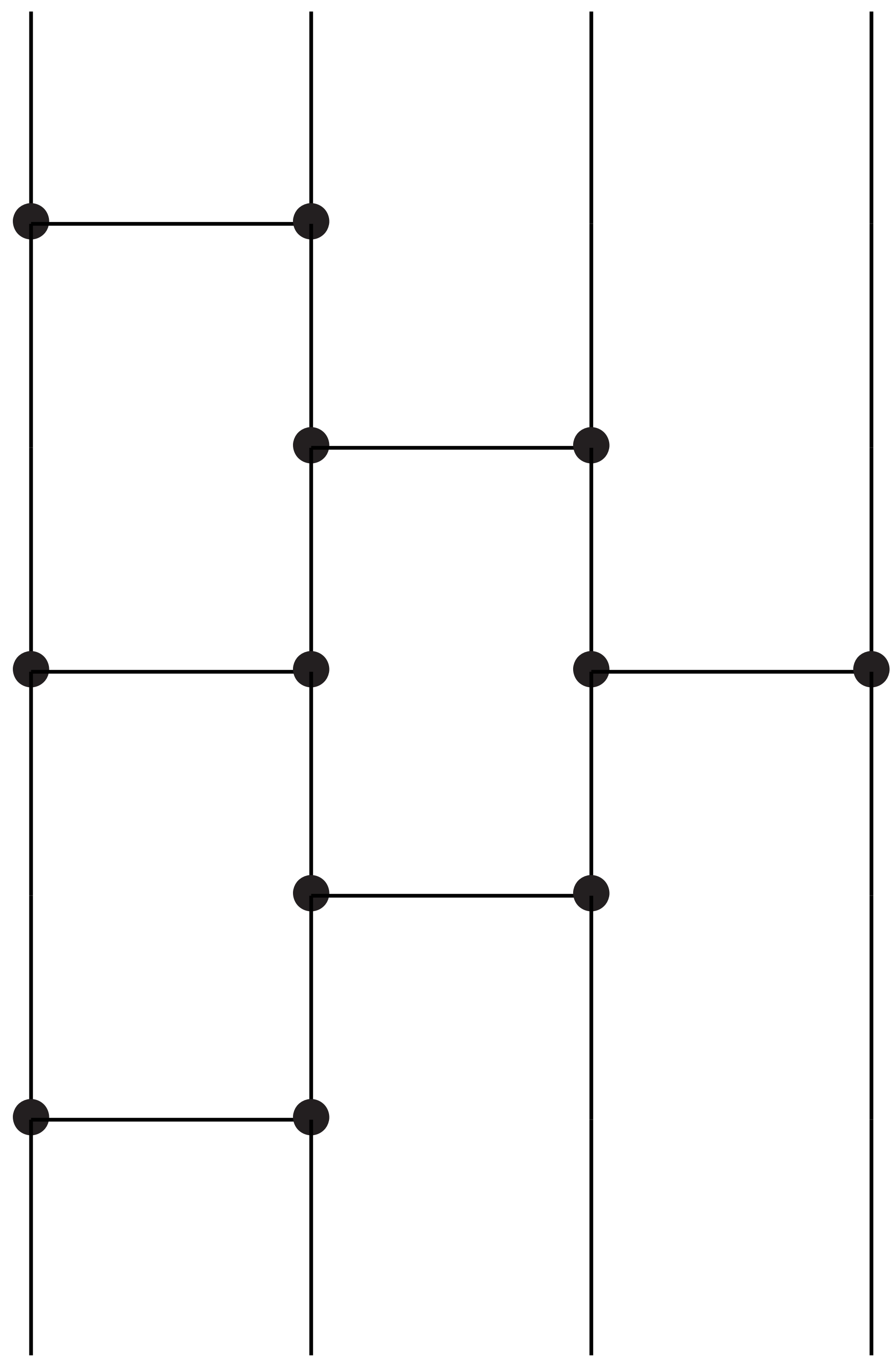

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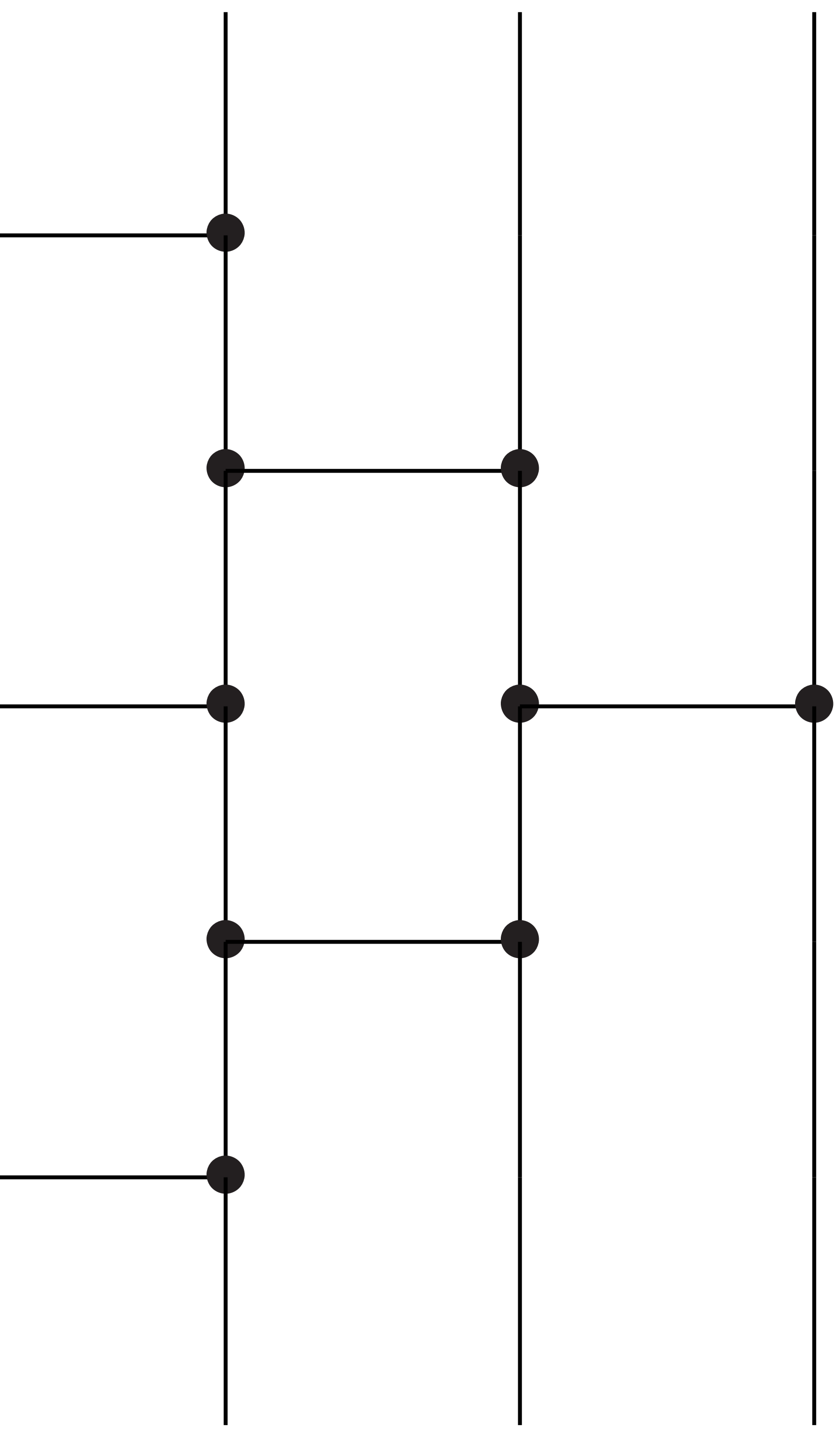

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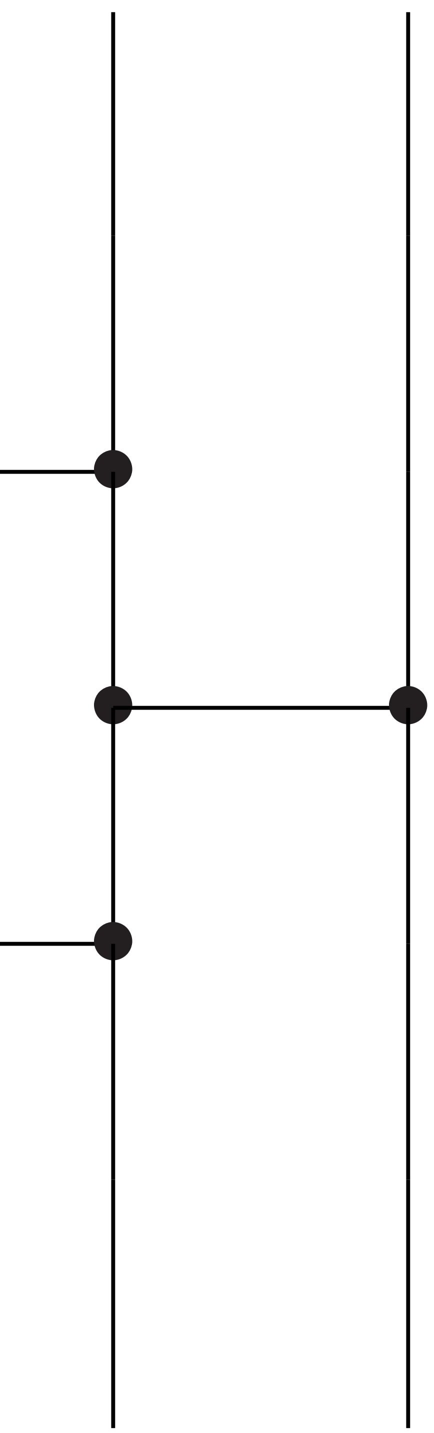

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```
void int32_sort(
{ int64 t,p,q,i;
  if (n < 2) ret
  t = 1;
  while (t < n -
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```
void int32_sort(int32 *x,
{ int64 t,p,q,i;
  if (n < 2) return;
  t = 1;
  while (t < n - t) t +=
  for (p = t;p > 0;p >>=
    for (i = 0;i < n - p;
      if (!(i & p))
        minmax(x+i,x+i+p)
    for (q = t;q > p;q >>
      for (i = 0;i < n -
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  if (n < 2) return;
  t = 1;
  while (t < n - t) t += t;
  for (p = t;p > 0;p >>= 1) {
    for (i = 0;i < n - p;++i)
      if (!(i & p))
        minmax(x+i,x+i+p);
    for (q = t;q > p;q >>= 1)
      for (i = 0;i < n - q;++i)
        if (!(i & p))
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  if (n < 2) return;
  t = 1;
  while (t < n - t) t += t;
  for (p = t;p > 0;p >>= 1) {
    for (i = 0;i < n - p;++i)
      if (!(i & p))
        minmax(x+i,x+i+p);
    for (q = t;q > p;q >>= 1)
      for (i = 0;i < n - q;++i)
        if (!(i & p))
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```
t32_sort(int32 *x,int64 n)
 t,p,q,i;
 < 2) return;
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 (t < n - t) t += t;
p = t;p > 0;p >>= 1) {
 (i = 0;i < n - p;++i)
f (!(i & p))
 minmax(x+i,x+i+p);
 (q = t;q > p;q >>= 1)
or (i = 0;i < n - q;++i)
 if (!(i & p))
   minmax(x+i+p,x+i+q);
```


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Answer: well-known trends in CPU design, reflecting fundamental hardware costs of various operations.

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Conditional branch: much slower.

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How can an $n(\log n)^2$ algorithm beat standard $n \log n$ algorithms?

Answer: well-known trends in CPU design, reflecting fundamental hardware costs of various operations.

Every cycle, Haswell core can do 8 “min” ops on 32-bit integers + 8 “max” ops on 32-bit integers.

Loading a 32-bit integer from a random address: much slower.

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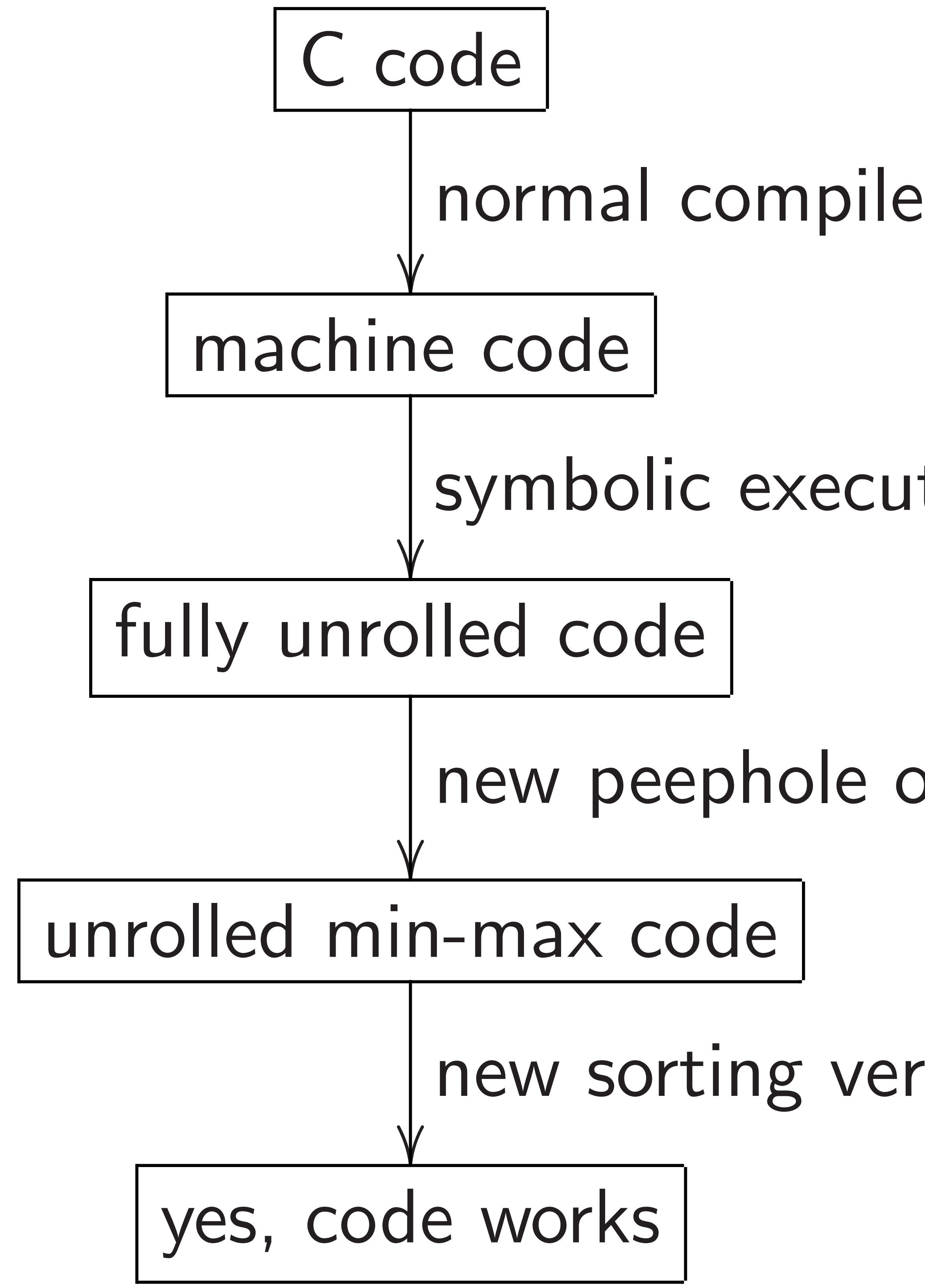

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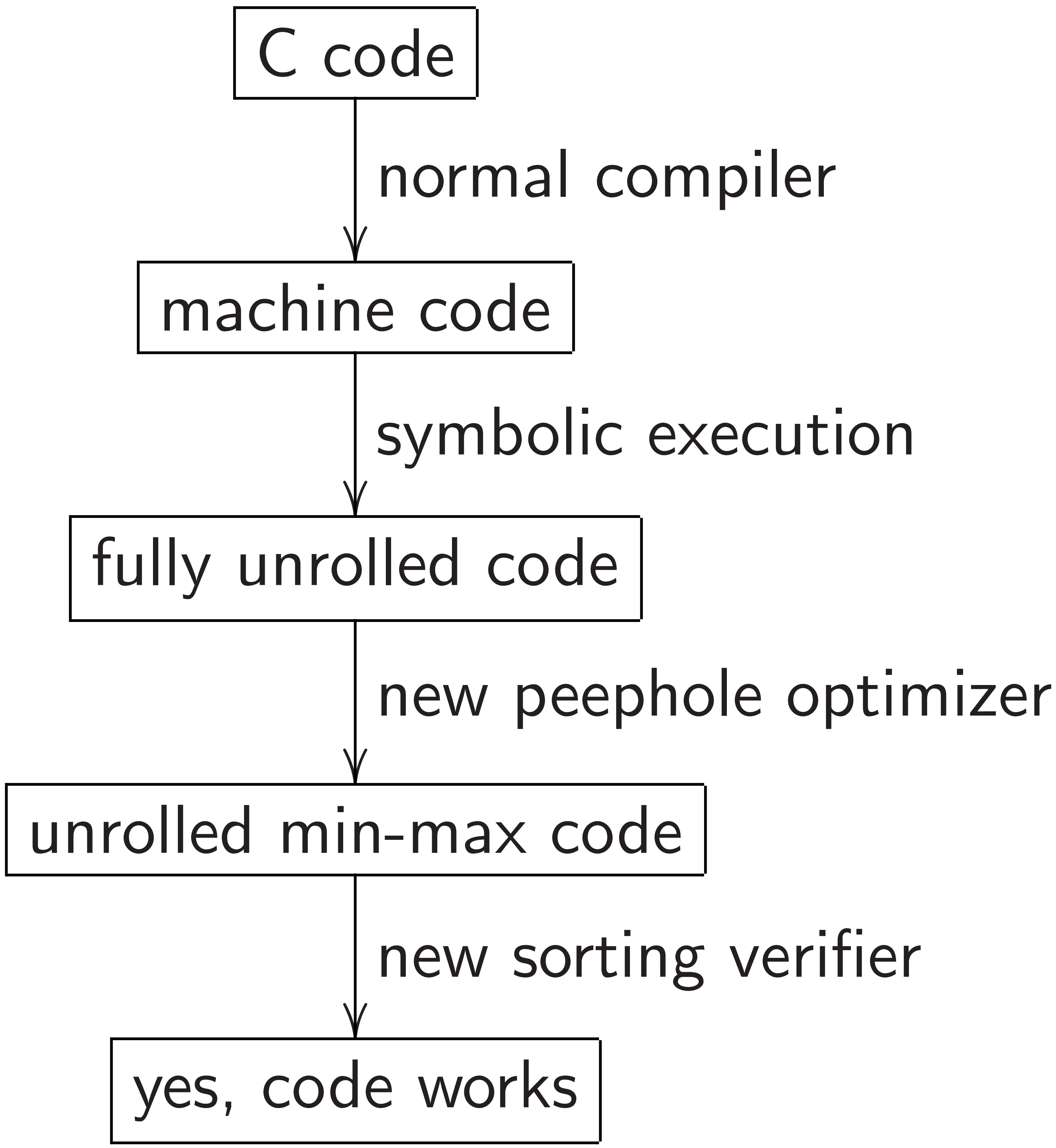

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Web site shows how to use the verification tools.

Next release planned: verified ARM NEON code.

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