CS350: Data Structures

Bloom Filters

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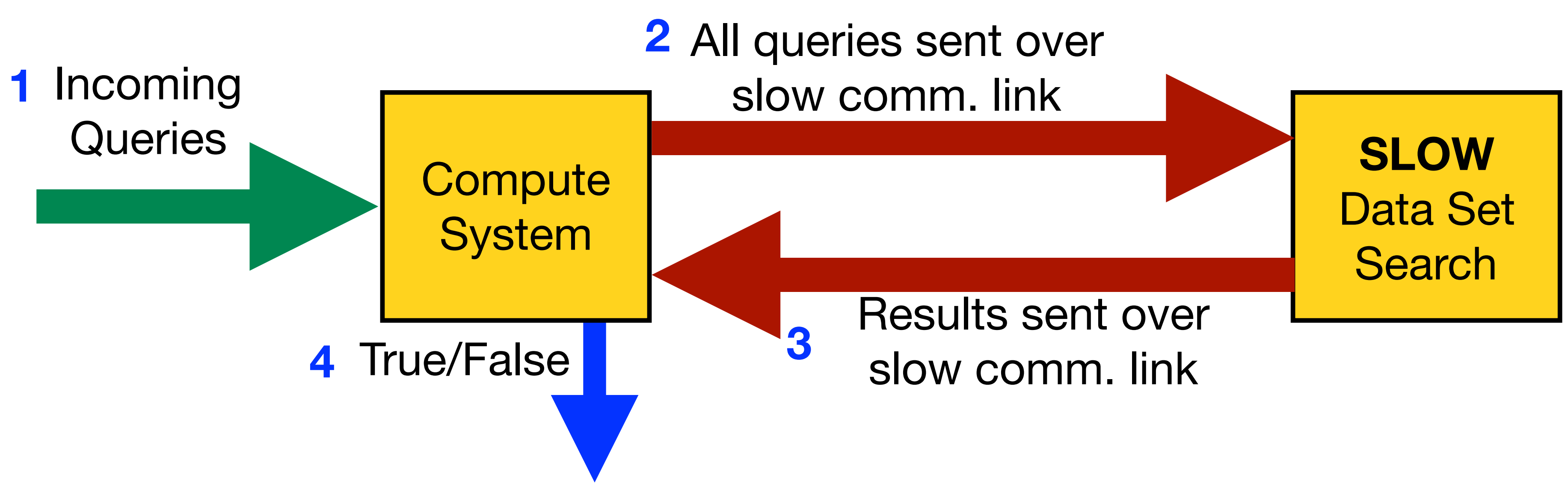
Bloom Filters

- **A space-efficient, probabilistic data structure used to see if a data element is a member of a data set**
  - A trie can also be used to check for membership in a set
- **Often used to speed up set queries by quickly filtering out all queries where the answer will definitely be 'not in set'**
  - Useful in systems where *actual* set membership can only be determined by:
    - searching a 'slow' data structure
    - reading data from a 'slow' memory
  - Don't access the 'slow' data structure/memory if you know the data isn't in there

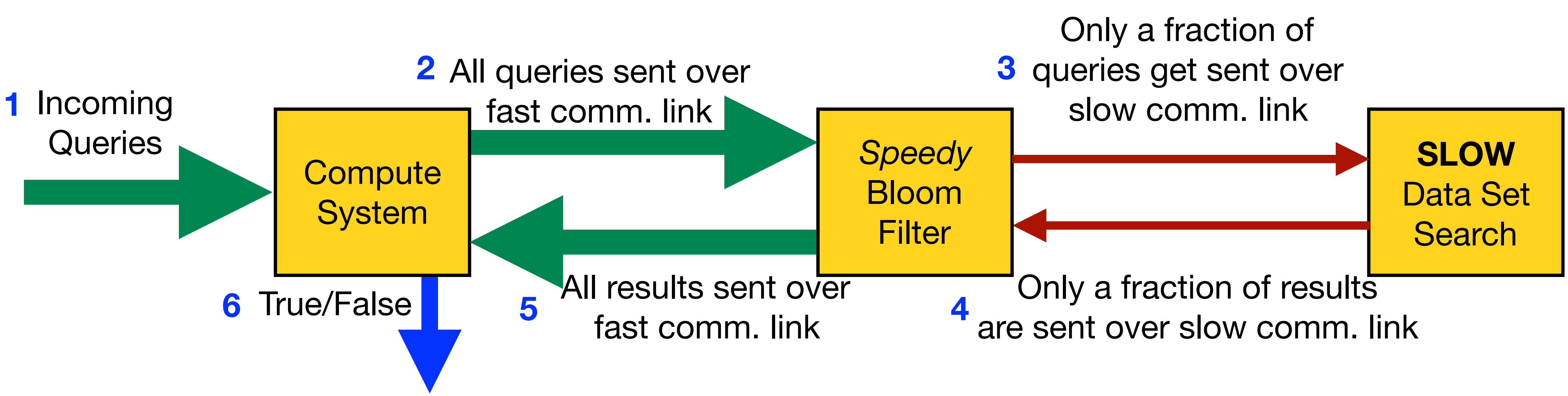
Query System Without Bloom Filters

- **A compute system requires a membership check for incoming data elements**
- **Possible problems:**
  - Communication link to main data structure/storage may be a slow link
  - Main data structure/storage may not have the performance necessary to service ALL queries
- **Solution:**
  - Only send queries to the main data structure/storage that have the possibility of existing in the data set



Query System With Bloom Filters

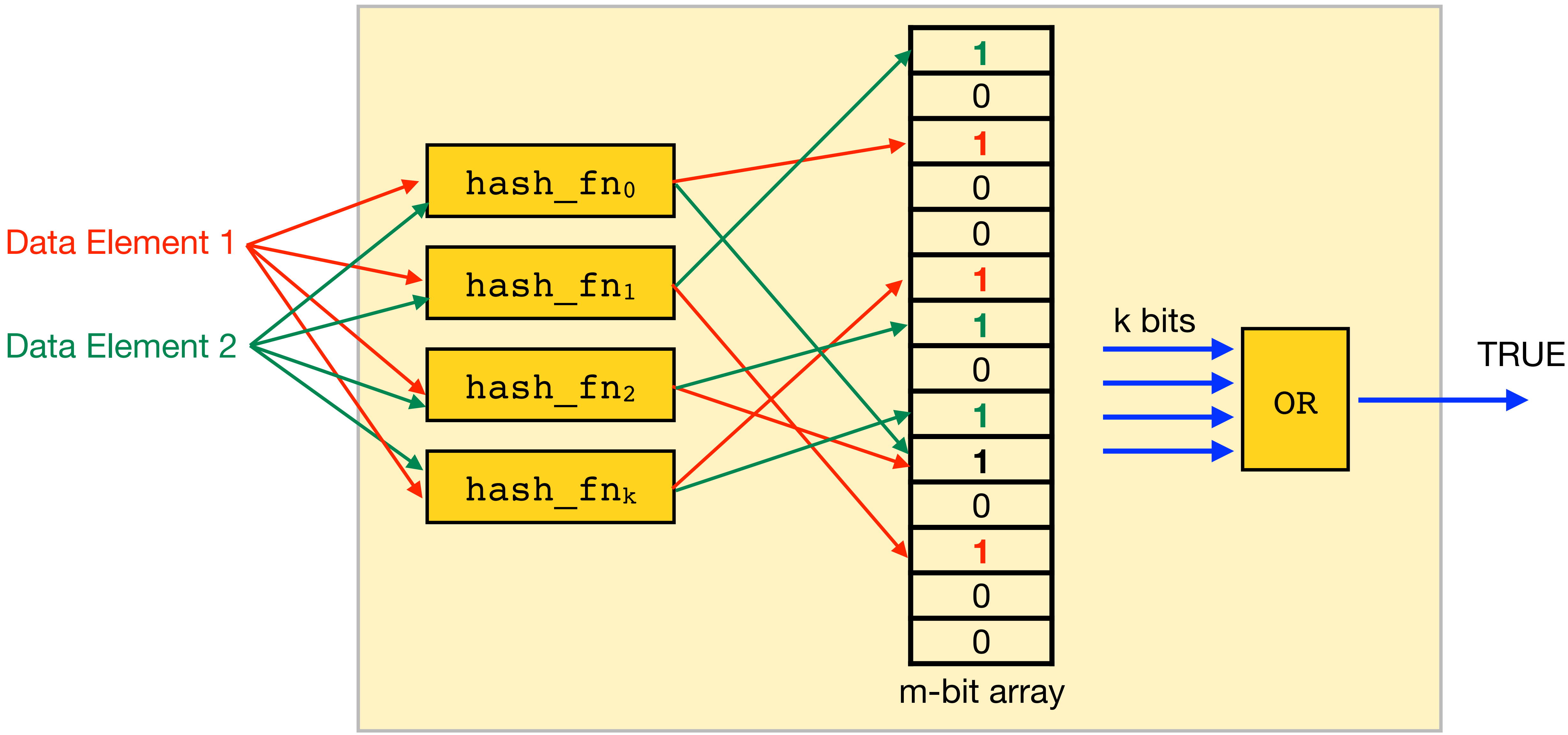
- **A compute system requires a membership check for incoming data elements**
- **Insert a Bloom filter into the data path**
  - Reduces the number of queries the need to be serviced by the slower communication links, data structures/storage
- **All queries are quickly sent to and serviced by the Bloom filter**
  - Bloom filter can quickly respond with a FALSE for data elements not in the set
  - For data elements that *might* be in the set, the query is sent to be serviced by the slower data set search



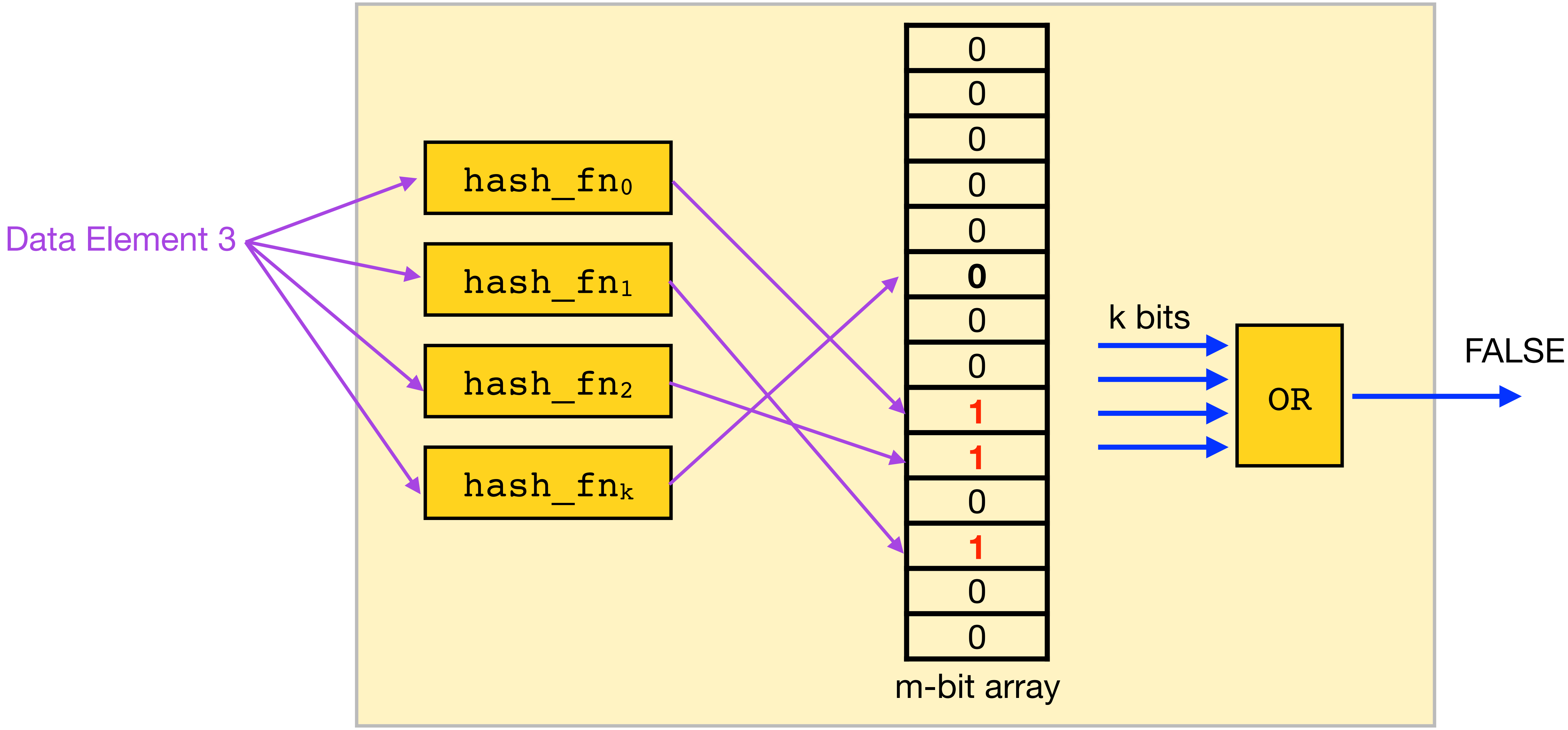
Bloom Filters

- **Utilizes multiple hash functions and an array of bits to define set**
  - Incoming data elements are hashed by ALL *k* hash functions
  - Each hash function generates an address that is used to lookup a single bit in the bit array
    - With *k* hash functions, *k* addresses are computed and *k* bits are read/set in the bit array
  - Each of the *k* bits is used to determine if a data element exists in the data set
    - If all *k* bits are 1, then the data element *might* exist
    - If any of the *k* bits are 0, then the data element definitely does not exist in the set

Checking Membership

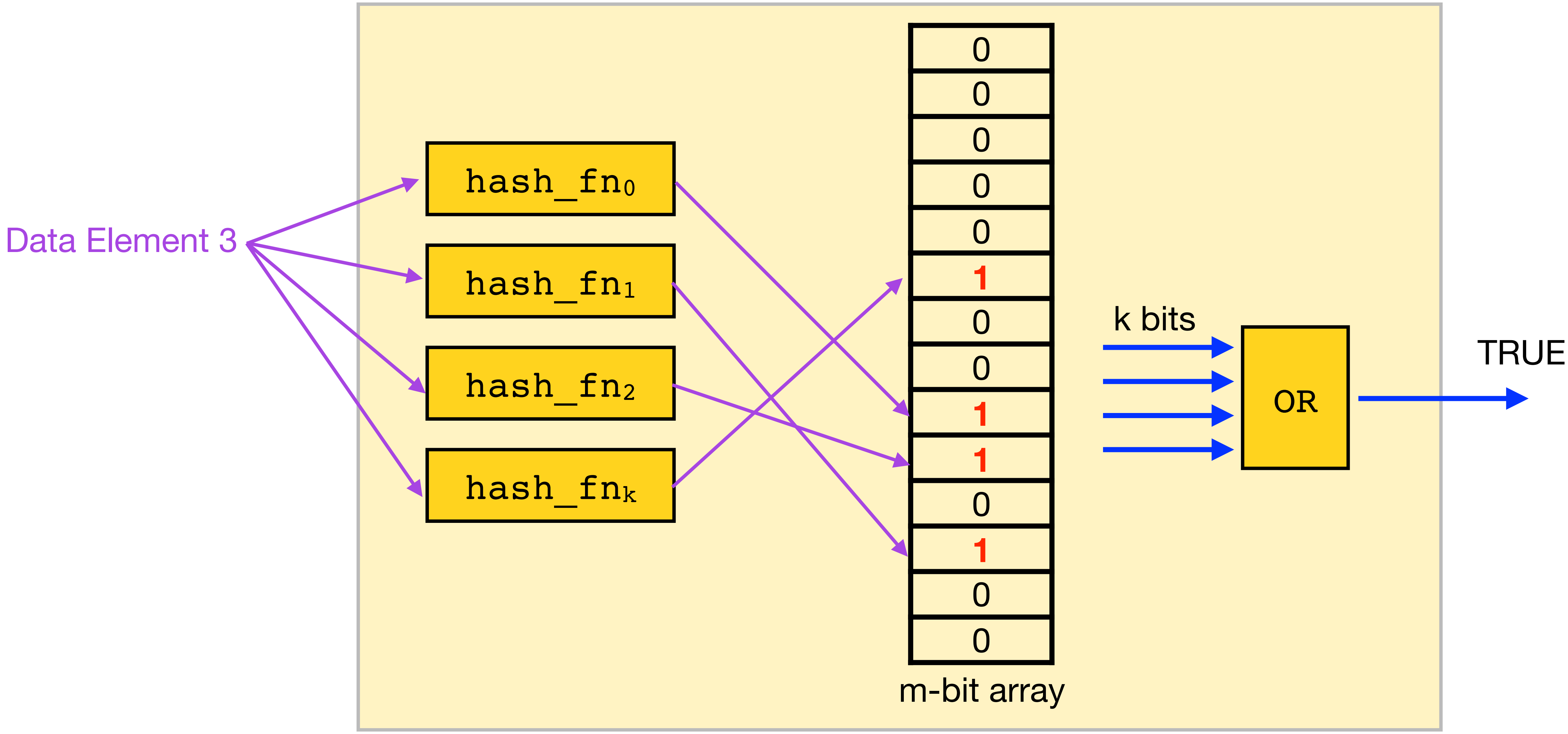


Checking Membership



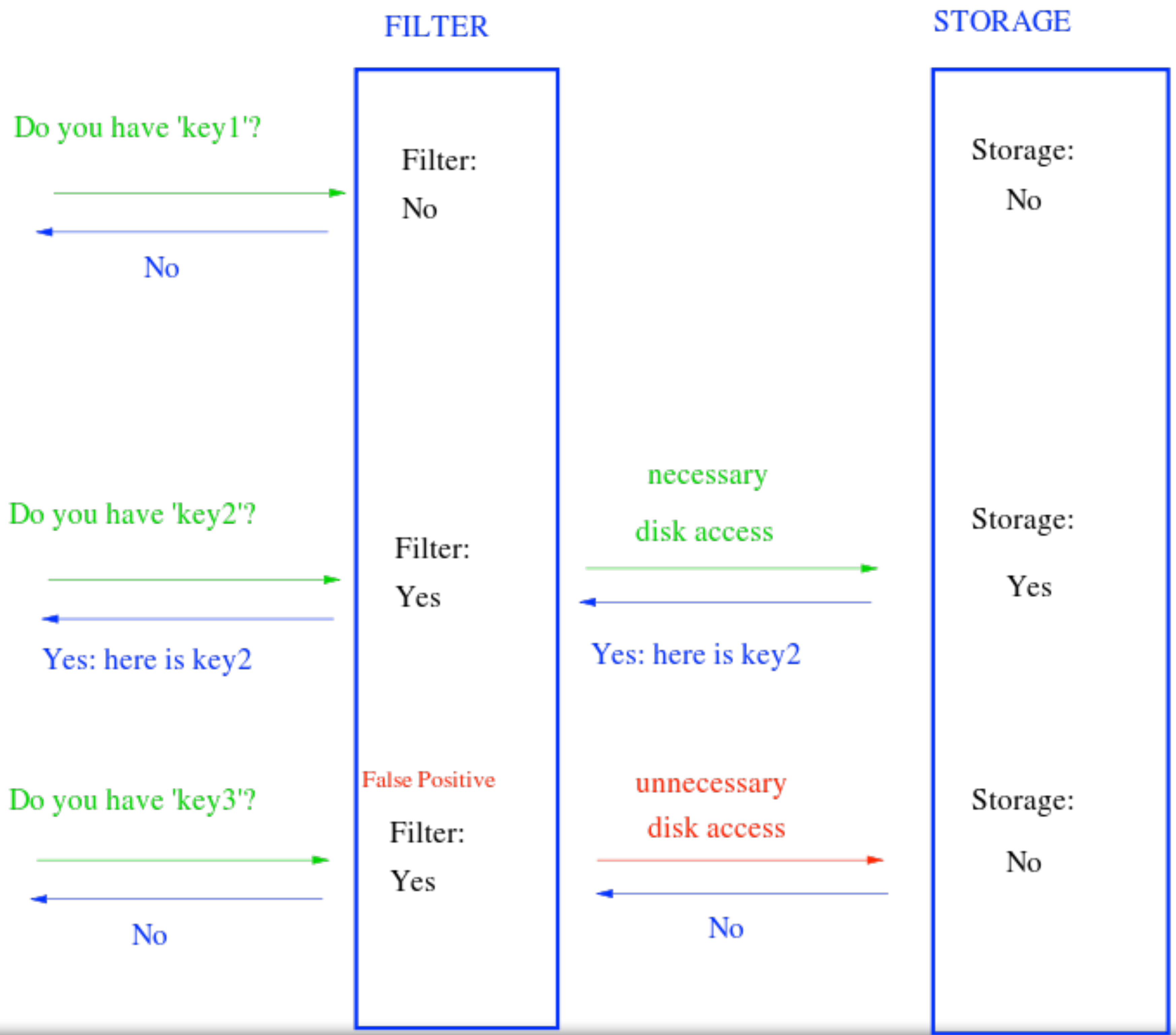
Red bits set by some other data element, not by data element 3

Checking Membership / False Positive



Red bits set by some other data element, not by data element 3

Checking Membership / Slow Storage Access



From Wikipedia

False Positives / False Negatives

- **Using more hash functions will result in fewer false positives**
- **Using a larger bit array will result in fewer false positives**
- **The more elements in the data set the greater the probability that a false positive will occur**
  - Just like the more elements in a hash table, the more likely a collision will occur
- **False negatives cannot happen in a Bloom filter**
  - If the data element was added to the filter, the filter will NEVER say the data doesn't exist

Insertion Into a Bloom Filter

- **Hash data element with *k* unique hash functions to compute *k* different addresses into the m-bit array**
- **Set *k* bits in m-bit array based on the results of the *k* hash functions**

```
bit_array[ hash_fn0(data) ] = 1;
bit_array[ hash_fn1(data) ] = 1;
bit_array[ hash_fn2(data) ] = 1;
bit_array[ hash_fn3(data) ] = 1;
```

- **Time complexity for insert is O(1)**

Checking for Membership in Filter

- **Hash data element with *k* unique hash functions to compute *k* different addresses into the m-bit array**

- **`AND` together *k* bits in m-bit array based on the results of the *k* hash functions**

```
return bit_array[ hash_fn0(data) ] &
       bit_array[ hash_fn1(data) ] &
       bit_array[ hash_fn2(data) ] &
       bit_array[ hash_fn3(data) ];
```

- **Time complexity for insert is O(1) for initial lookup**
    - Does not include lookup in slower storage
    - Slower storage access would have its own complexity

Deleting a Data Element

- **Elements cannot be deleted from a standard Bloom filter**
  - Cannot clear bits in the bit array since multiple data elements may have ‘set’ the same bit
  - Unsetting a bit may have the unintended consequence of removing other data elements from the filter

- **A variation of the Bloom Filter exists that allows deletion**
  - Counting Bloom Filter uses small counters at each hash location instead of a single bit
    - When inserting data elements, increase counter
    - When deleting data elements, decrease counter
    - When checking membership, check to see that count is != 0

Some Math

- **The probability that a false positive is reported by a Bloom Filter is approximated by the following:**

$$f \approx \left(1 - e^{\frac{-nk}{m}}\right)^k$$

  - where

    f is the probability of a false positive
    m is the size of the bit-array
    k is the number of hash functions
    n is the number data elements inserted into the filter

- **Decrease probability of false positive by increasing either *m* or *k***

- **Can *tune* desired false positive based on system resources**