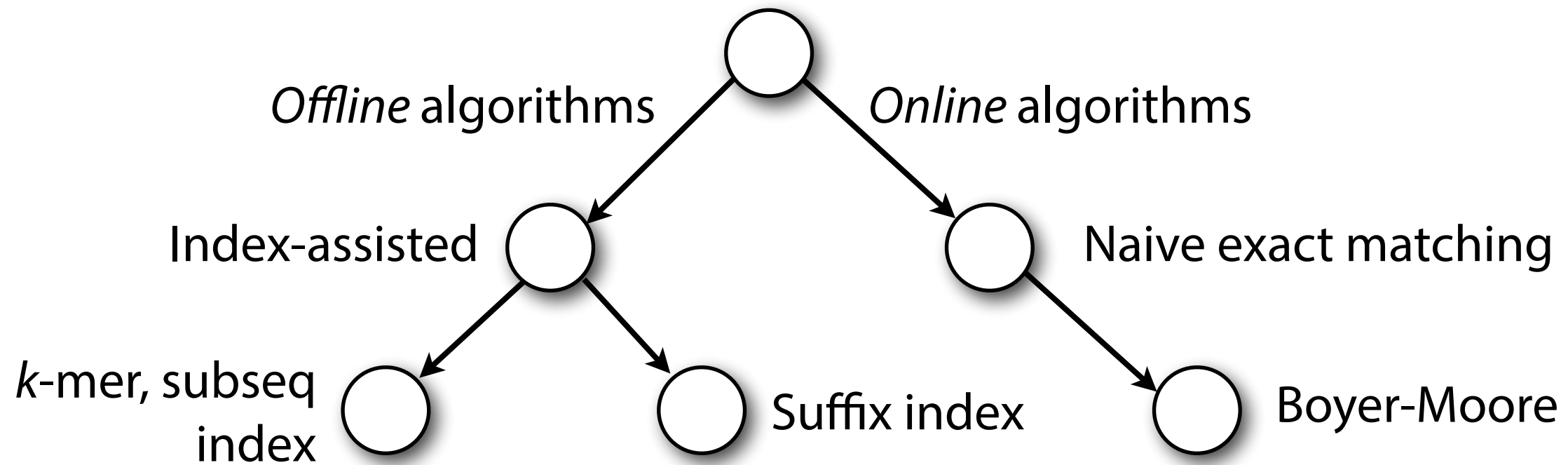


Approximate matching



All for exact matching

Approximate matching

Read

CTCAAACCTCCTGACCTTTGGTGATCCACCCGCCTAGGCCTTC

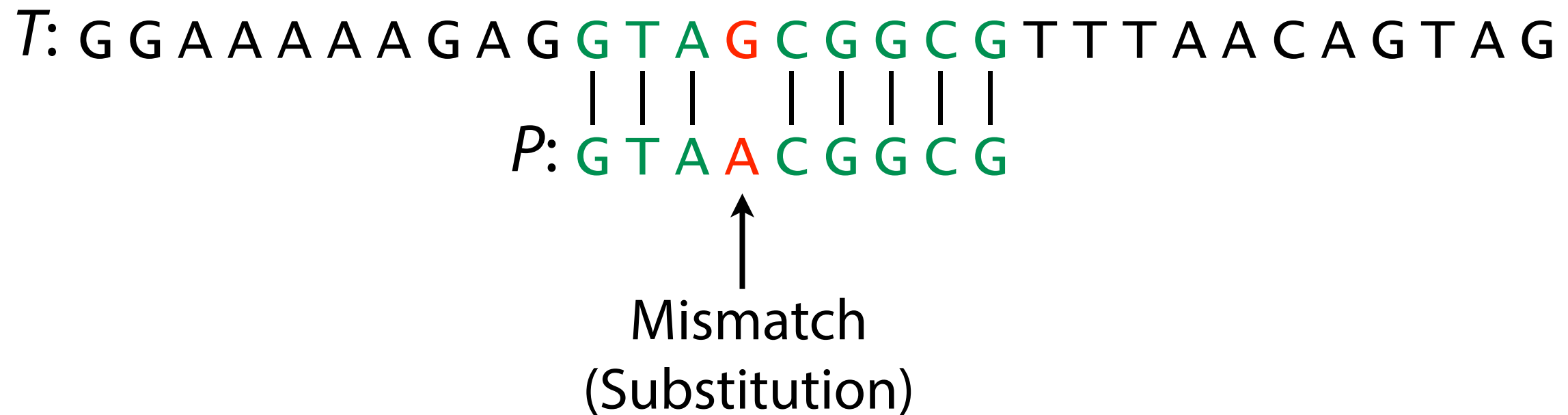
Reference

GATCACAGGTCTATCACCTATTAACCACTCACGGGAGCTCTCCATGCATTTGGTATTTT
CGTCTGGGGGGTATGCACGCGATAGCATTGCGAGACGCTGGAGCCGGAGCACCTATGTC
GCAGTATCTGTCTTTGATTCTGCCTCATCCTATTATTTATCGCACCTACGTTCAATATT
ACAGGCGAACATACTTACTAAAGTGTGTTAATTAATTAATGCTTGTAGGACATAATAATA
ACAATTGAATGTCTGCACAGCCACTTTCCACACAGACATCATAACAAAAAATTTCCACCA
AACCCCCCTCCCCGCTTCTGGCCACAGCACTAAACAGCTCTGCCAAACCCCAAAA
ACAAAGAACCCTAACACCAGCCTAACCAATTTCAAATTTTATCTTTGGCGGTATGCAC
TTTTAACAGTCACCCCCCACTAACCAATTTATTTTCCCCTCCCCTTCCATACTACTAAT
CTCATCAATACAACCCCCGCCCCTTACCCAGCACACACACACCCCTTAAACCCATA
CCCCGAACCAACCAAAACCCCAAAAGCACCCCCCAGTTTATGTAGCTTACCTCCTCAA
GCAATACACTGACCCGCTCAAACCTTGGATTTTGGATCCACCCAGCGCTTGGCCTAAA
CTAGCCTTTCTATTAGCTCTTAGAAGATTACACATGCAAGCATCCCCGCTCCAGTGAGT
TCACCCTCTAAATCACCACGATCAAGGAACAAGCATCAAGCACGCAGCAATGCAGCTC
AAAACGCTTAGCCTAGCCACACCCTCACGGGAAACAGCAGTGATTAACCTTAGCAATAA
ACGAAAGTTTAACTAAGCTATACTTACCCAGGGTTGGTCAATTTCTGCTCCAGCCACCGC
GGTCACACGATTAACCCAAGTCAATGAAGCCGGCGTAAAGAGTGTTTAGATCACCCCC
TCCCCAATAAAGCTAAAACTCACCTGATTTGTAAAAAACTCCAGTTTACAAAAATAGAC
TACGAAAGTGGCTTTAACATATCTGAACAACAATAGCTAAGACCTGGGATTAGA
TACCCCACTATGCTTAGCCCTAAACCTCAACAGCTTAAACAATAGCCAGAA
CACTACGAGCCACAGCTTAAAACTCAAAGGACCTGGCGGTGCTTCATCTAGAGG
AGCCTGTTCTGTAATCGATAAACCCCGATCAACCTCACCACCTCTTGCTTATATA
CCGCCATCTTCAGCAAACCCTGATGAAGGCTACAAAGTAAGCGCAAGTACCTAG
ACGTTAGGTCAAGGTGTAGCCCATGAGGTGGCAAGAAATGGGCTACATTTTC
AAAACCTACGATAGCCCTTATGAACTTAAGGGTGAAGGTGGATTTAGCAGTAA
AGTAGAGTGCTTAGTTGAACAGGGCCCTGAAGCGCGTACACACCCGCCGTACCCCT
AAGTATACTTCAAAGGACATTTAACTAAAACCCCTACGCATTTATATAGAGGAGACA
CGTAACCTCAAACCTCCTGCCTTTGGTGATCCACCCGCCTTGGCCTACCTGCATAATGAAG
AAGCACCCAACCTTACACTTAGGAGATTTCAACTTAACTTGACCGCTCTGAGCTAAACCTA
GCCCCAAACCCACTCCACCTTACTACCAGACAACCTTAGCCAAACCATTTACCCAAATAA
AGTATAGGCGATAGAAATTGAAACCTGGCGCAATAGATATAGTACCGCAAGGGAAAGATG
AAAAATTATAACCAAGCATAATATAGCAAGGACTAACCCTTATACCTTCTGCATAATGAA
TTAACTAGAAATAACTTTGCAAGGAGAGCCAAAGCTAAGACCCCCGAAACCAGACGAGCT
ACCTAAGAACAGCTAAAAGAGCACACCCGTCTATGTAGCAAAATAGTGGGAAGATTTATA
GGTAGAGGCGACAAACCTACCGAGCCTGGTGATAGCTGGTTGTCCAAGATAGAATCTTAG
TTCAACTTTAAATTTGCCCACAGAACCCTCTAAATCCCCTTGTAATTTAACTGTTAGTC
CAAAGAGGAACAGCTCTTTGGGACACTAGGAAAAAAACCTTGTAAGAGAGAGTAAAAAATTTA

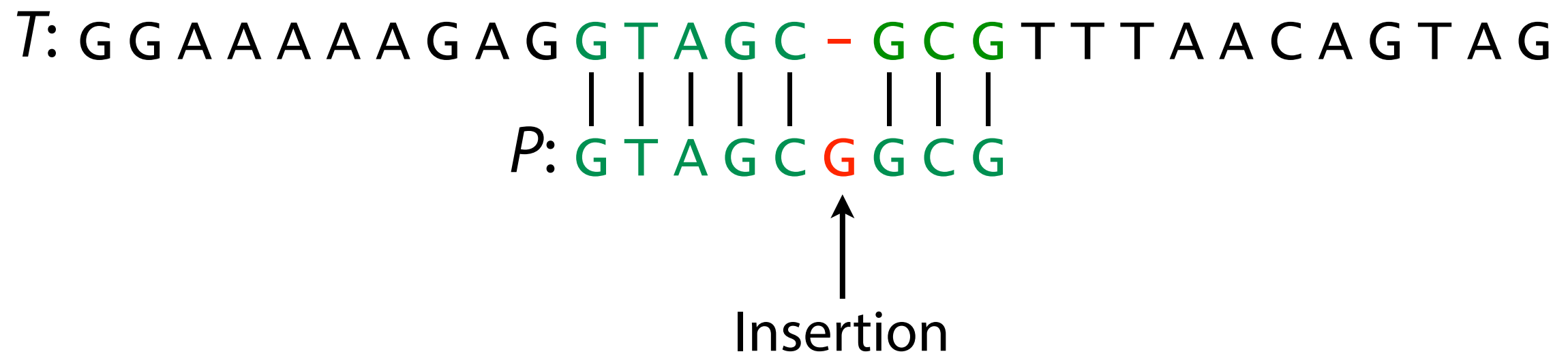
Differences between read and reference occur because of...

1. Sequencing error
2. Natural variation

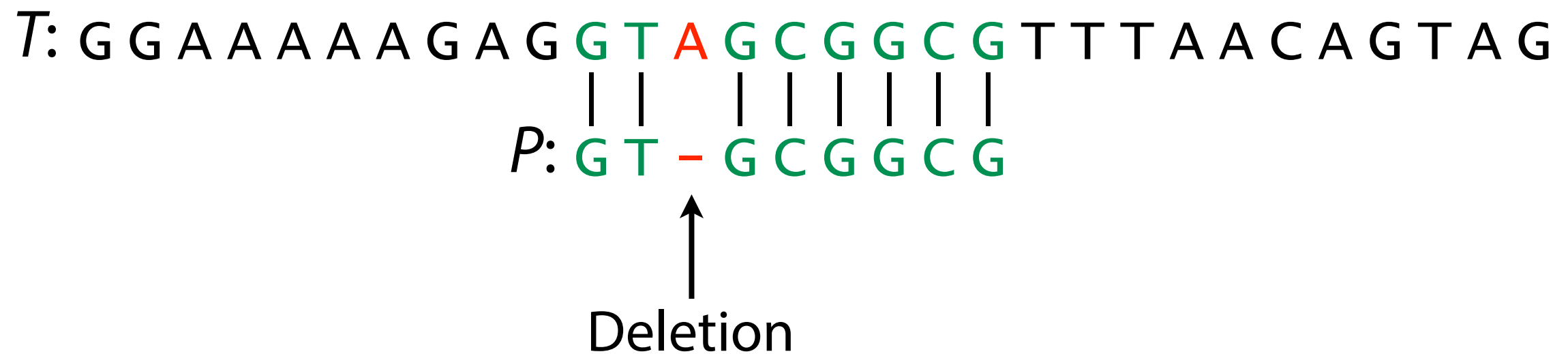
Approximate matching



Approximate matching



Approximate matching



Hamming distance

For X & Y where $|X| = |Y|$, *hamming distance* =
minimum # substitutions needed to turn one into the other

$X:$	G	A	G	G	T	A	G	C	G	G	C	G	T	T	T	A	A	C
$Y:$	G	T	G	G	T	A	A	C	G	G	G	G	T	T	T	A	A	C

Hamming distance = 3

Edit distance

(AKA Levenshtein distance)

For X & Y , *edit distance* = minimum # edits (substitutions, insertions, deletions) needed to turn one into the other

$X:$	T	G	G	C	C	G	C	G	C	A	A	A	A	A	C	A	G	C
$Y:$	T	G	A	C	C	G	C	G	C	A	A	A	A	-	C	A	G	C

Edit distance = 2

$X:$	G	C	G	T	A	T	G	C	G	G	C	T	A	-	A	C	G	C
$Y:$	G	C	-	T	A	T	G	C	G	G	C	T	A	T	A	C	G	C

Edit distance = 2

Approximate matching

```
def naive(p, t):  
    occurrences = []  
    for i in xrange(len(t) - len(p) + 1): # Loop over alignments  
        match = True  
        for j in xrange(len(p)): # Loop over characters  
            if t[i+j] != p[j]: # compare characters  
                match = False # mismatch; reject alignment  
                break  
        if match:  
            occurrences.append(i) # all chars matched; record  
    return occurrences
```

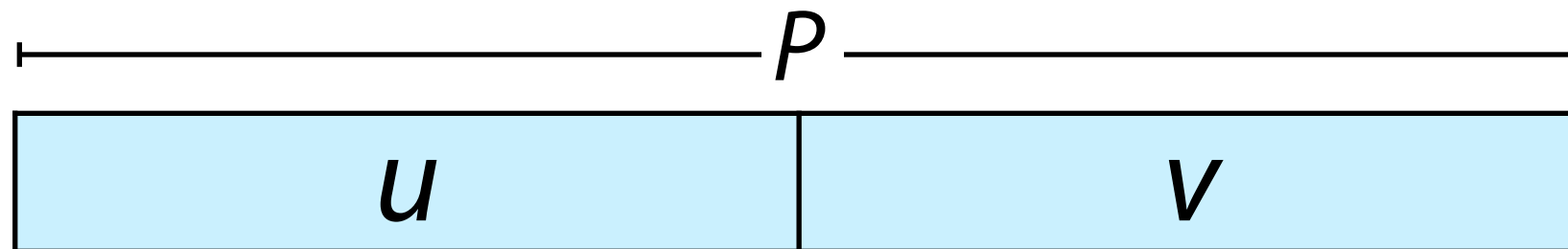

Approximate matching

```
def naiveHamming(p, t, maxDistance):
    occurrences = []
    for i in xrange(len(t) - len(p) + 1): # Loop over alignments
        nmm = 0
        match = True
        for j in xrange(len(p)):          # Loop over characters
            if t[i+j] != p[j]:            # compare characters
                nmm += 1                  # mismatch
            if nmm > maxDistance:          # exceeded max hamming dist
                break
        if nmm <= maxDistance:
            occurrences.append(i)          # approximate match
    return occurrences
```

Approximate matching

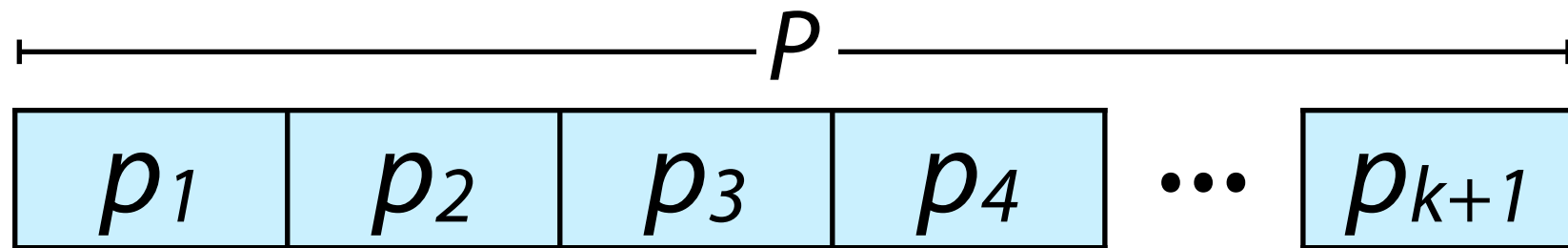
Wanted: way to apply exact matching algorithms to approximate matching problems

Approximate matching



If P occurs in T with 1 edit, then u or v appears with no edits

Approximate matching



If P occurs in T with up to k edits, then at least one of p_1, p_2, \dots, p_{k+1} must appear with 0 edits

Approximate matching



Approximate matching

Approximate Boyer-Moore performance

	Boyer-Moore, exact			Boyer-Moore, ≤ 1 mismatch with pigeonhole			Boyer-Moore, ≤ 2 mismatches with pigeonhole		
	# character comparisons	wall clock time	# matches	# character comparisons	wall clock time	# matches	# character comparisons	wall clock time	# matches
P: "tomorrow" T: Shakespeare's complete works	786 K	1.91 s	17	3.05 M	7.73 s	24	6.98 M	16.83 s	382
P: 50 nt string from Alu repeat* T: Human reference (hg19) chromosome 1	32.5 M	67.21 s	336	107 M	209 s	1,045	171 M	328 s	2,798

* GCGCGGTGGCTCACGCCTGTAATCCCAGCACTTTGGGAGGCCGAGGCGGG