Parallel External Memory Suffix Sorting

Juha Kärkkäinen   Dominik Kempa   Simon J. Puglisi

University of Helsinki, Finland

CPM, Ischia, July 2015

Outline

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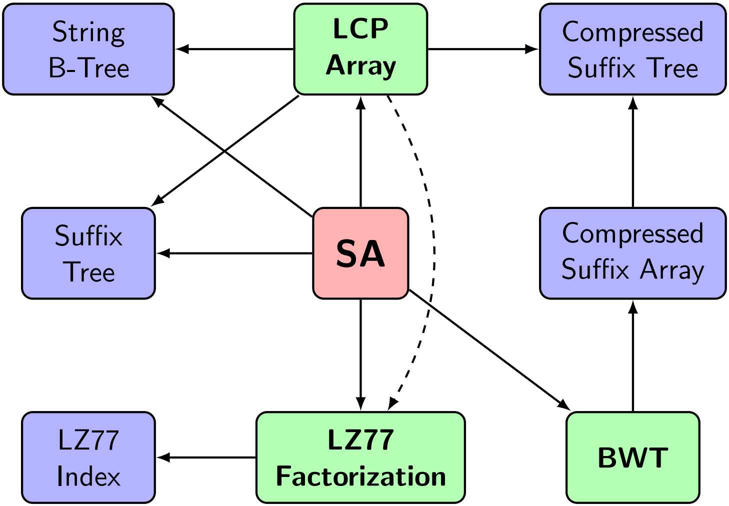
1. Introduction and Background
2. Internal memory SACA
3. External memory SACA

Central Role of Suffix Array (SA)



Suffix Array Construction

Suffix array construction algorithm (SACA):

Sort all suffixes of a text lexicographically

SA	
6	`$`
5	`a$`
3	`ana$`
1	`anana$`
0	`banana$`
4	`na$`
2	`nana$`

	Internal memory	External memory
Sequential	• Manber, Myers (1993) • Sadakane (1998) • Itoh, Tanaka (1999) • Larsson, Sadakane (1999) • Manzini, Ferragina (2002,2004) • Burkhardt, Kärkkäinen (2003) • Kärkkäinen, Sanders, Burkhardt (2003,2006) • Kim, Sim, Park, Park (2003,2005) • Ko, Aluru (2003,2005) • Hon, Sadakane, Sung (2003,2009) • Schürmann, Stoye (2005,2007) • Maniscalco, Puglisi (2007) • divsufsort: Mori (2008) • Nong, Zhang, Chan (2011) • Nong (2013)	• Gonnet, Baeza-Yates, Snider (1987,1992) • Crauser, Ferragina (1999,2002) • Kärkkäinen, Sanders, Burkhardt (2003,2006) • Dementiev, Kärkkäinen, Mehnert, Sanders (2005,2008) • Ferragina, Gagie, Manzini (2010,2012) • Beller, Zwerger, Gog, Ohlebusch (2013) • eSAIS: Bingmann, Fischer, Osipov (2013) • SAscan: Kärkkäinen, K (2014) • Tischler (2014) • Nong, Chan, Zhang, Guan (2014) • Nong, Chan, Hu, Wu (2015)
Parallel	• Kulla, Sanders (2006,2007) • pDC3: Blelloch, Shun (2011) • Osipov (2012) • Deo, Keely (2013) • pSAscan: This paper	• pSAscan: This paper

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Parallel

- Kulla, Sanders (2006,2007)
- pDC3: Blelloch, Shun (2011)
- Osipov (2012)
- Deo, Keely (2013)
- pSAscan: This paper

External memory

Sequential

- Gonnet, Baeza-Yates, Snider (1987,1992)
- Crauser, Ferragina (1999,2002)
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Parallel

- pSAscan: This paper

divsufsort

- Currently, the fastest sequential internal memory SACA
- Time complexity: $\mathcal{O}(n \log n)$
- Available 32- and 64-bit versions using $5n$ and $9n$ bytes of RAM

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pDC3

- Parallel version of DC3 algorithm of Kärkkäinen, Sanders, Burkhardt (2003,2006)
- Fastest parallel SACA multi-core architecture
- Optimal $\mathcal{O}(n)$ work
- Implementation by Blelloch and Shun
- RAM usage: $21n$ (32-bit), $41n$ (64-bit)
- (divsufsort: $5n$ (32-bit), $9n$ (64-bit))

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SAscan: general overview

1. Divide text into blocks
2. Construct SA for each block
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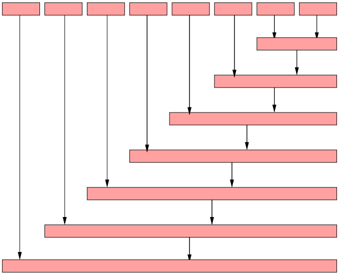
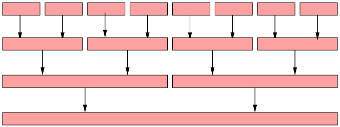
    - multiple merge schedules possible



Unbalanced merge



Fully balanced merge

SAscan: parallel in-RAM version

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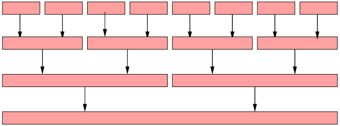
   - how to parallelize?



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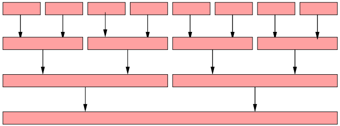
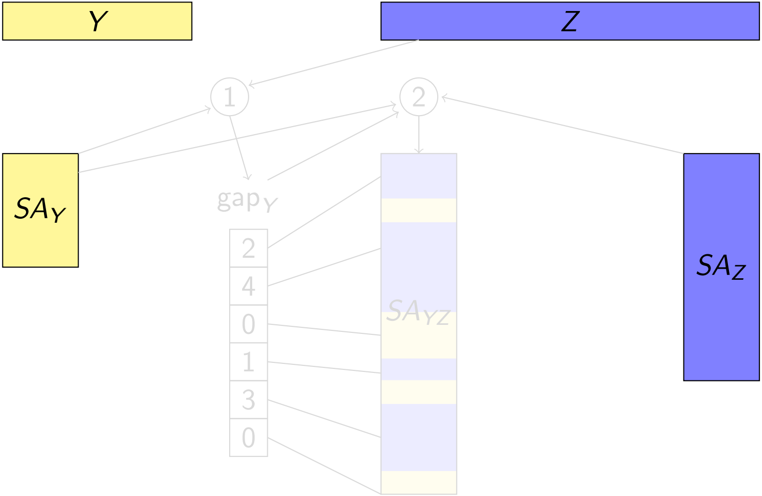


Merging SA of two blocks



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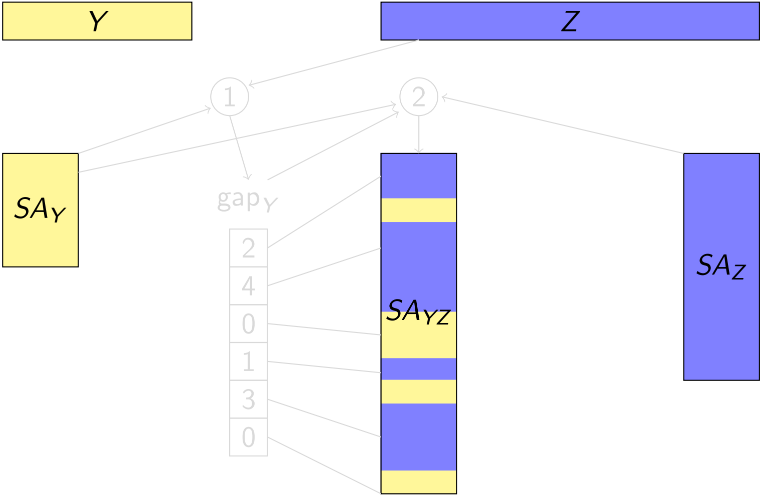

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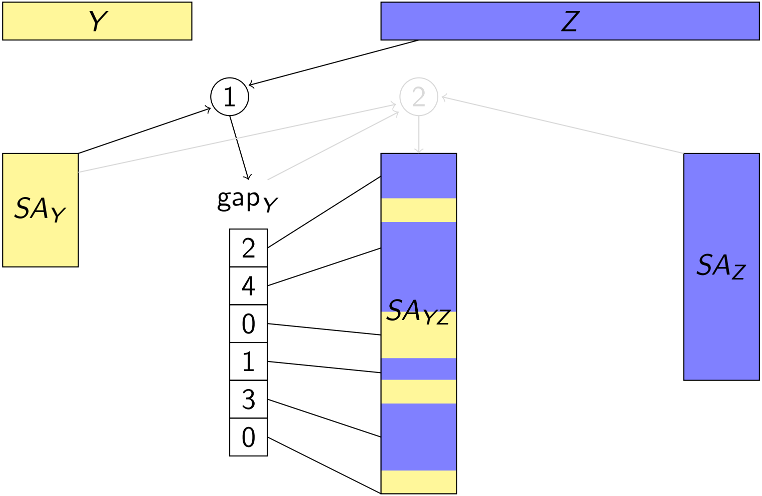

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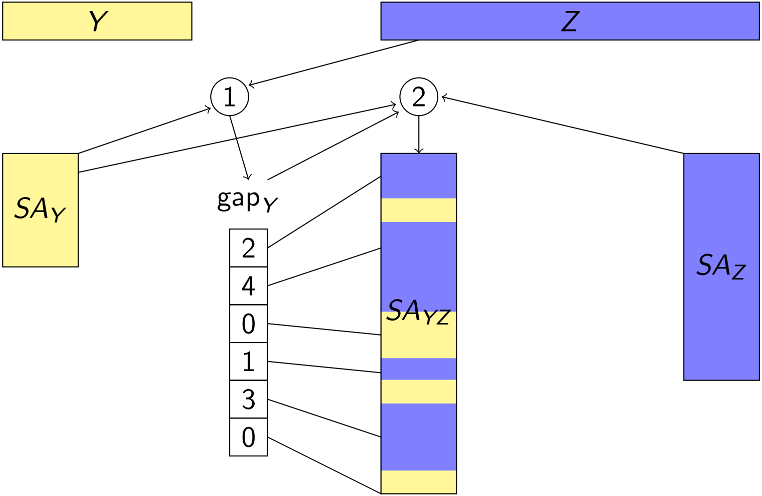

Merging SA of two blocks: parallel in-RAM version

1. $SA_Y + Z \rightarrow \mathrm{gap}_Y$
   - backward search with Y as text and Z as pattern [Ferragina, Gagie & Manzini (2010,2012)]
   - key property: needs rank data structure on BWT of Y
   - parallelization: start backward search from multiple positions
2. $SA_Y + SA_Z + \mathrm{gap}_Y \rightarrow SA_{YZ}$
   - parallelization: possible but complex, details omitted

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Internal memory pSAscan - summary

- Work: $\mathcal{O}(n \log p)$
- Space usage
  - $9n$ (32-bit), $10n$ (40-bit)
  - (pDC3: $21n$ (32-bit), $41n$ (64-bit))

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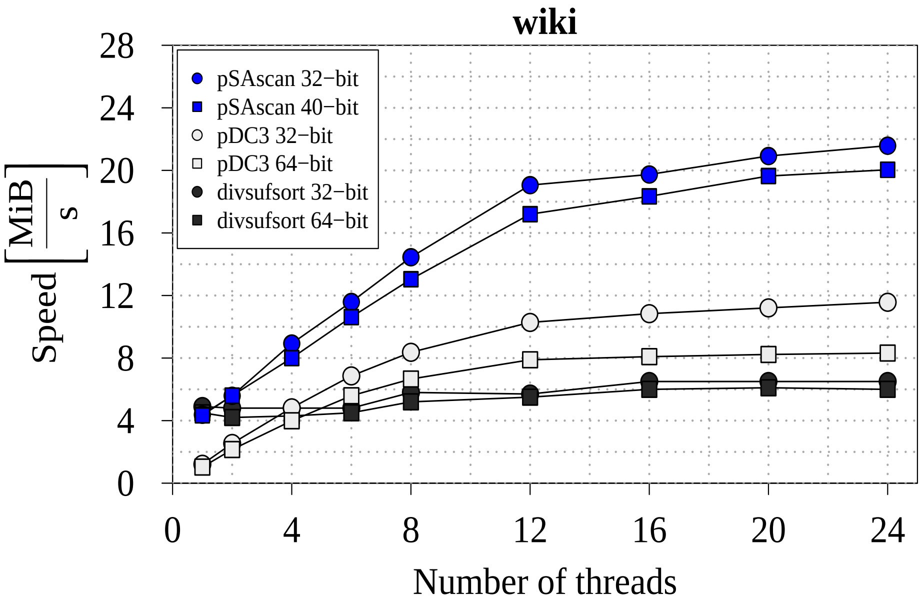
Experiments

(comparison of internal memory parallel suffix array construction algorithms)


wiki
pSAscan 32−bit
pSAscan 40−bit
pDC3 32−bit
pDC3 64−bit
divsufsort 32−bit
divsufsort 64−bit
Speed [MiB/s]
0
4
8
12
16
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Number of threads
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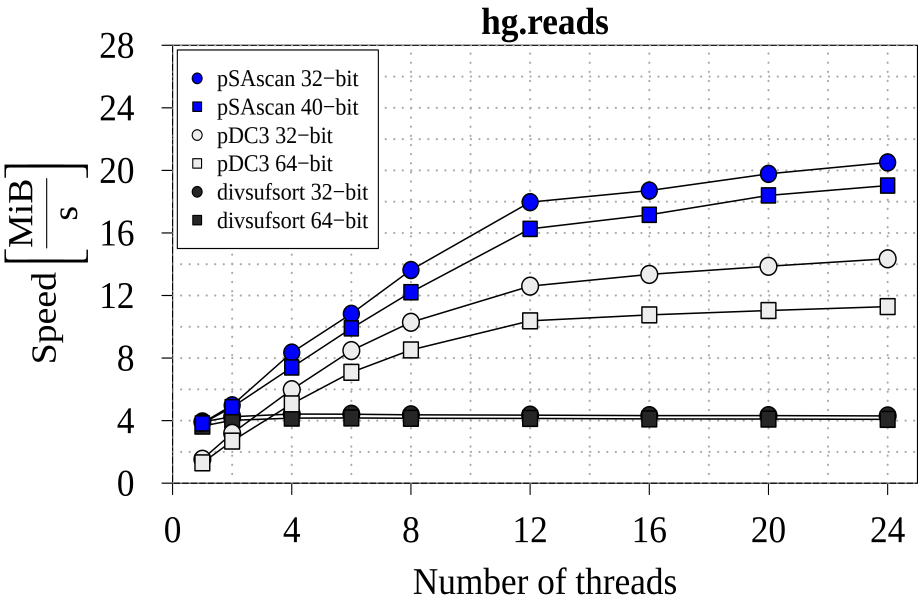

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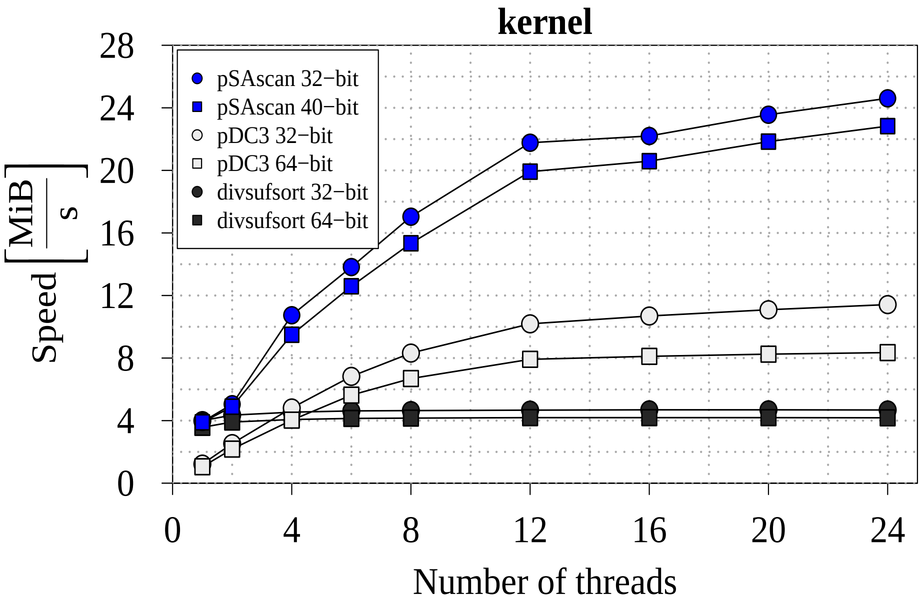

kernel
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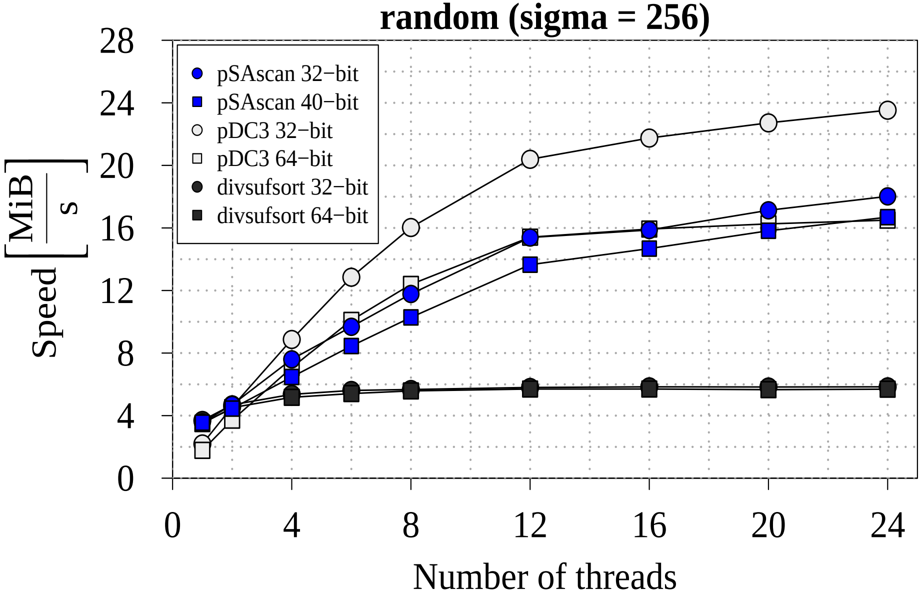
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eSAIS

- Optimal $\mathcal{O}(\mathrm{sort}(n))$ I/O complexity
  - $\mathrm{sort}(n)$ = complexity of sorting n integers
  - $\mathcal{O}\left(\frac{n}{B}\log_{M/B}\frac{n}{B}\right)$ I/Os
  - M = size of RAM, B = size of disk block (in units of $\log n$ bits)
- Implementation by Bingmann, Fischer & Osipov (2013)
- $28n$ bytes of disk space
  - n bytes for input
  - $5n$ bytes output

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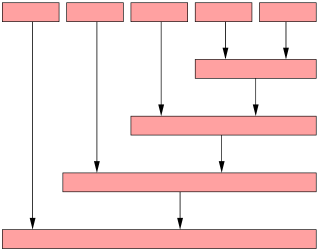
SAscan: EM version

1. Divide text into blocks
   - small enough for RAM processing
2. Construct SA for each block in RAM
3. Merge each block SA into full SA
   - key property: backward search needs rank data structure on BWT of left hand-size block $\implies$ unbalanced merging



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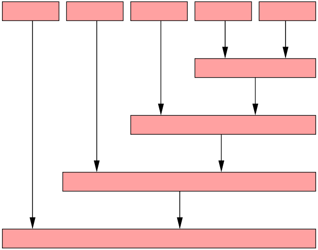

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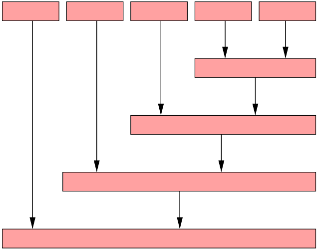

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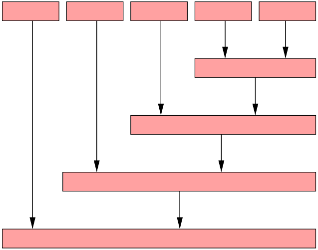

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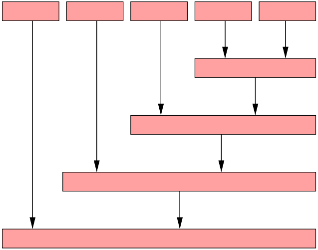

SAscan: EM version

- $\Theta(n/M)$ blocks
- Time and I/O proportional to n^2/M
- Fastest SACA when

$$\frac{\text{text size}}{\text{RAM size}} < 5$$

- Lightweight w.r.t. disk space, uses $7.5n$ bytes
    - eSAIS: $28n$

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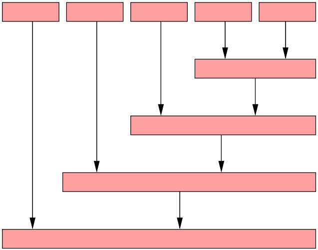

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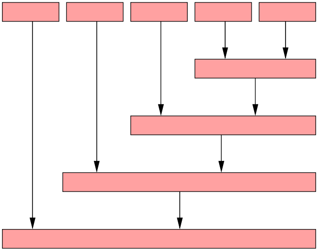

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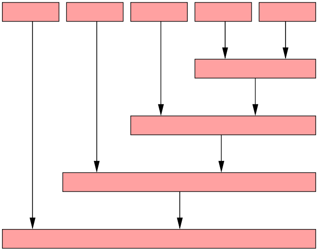

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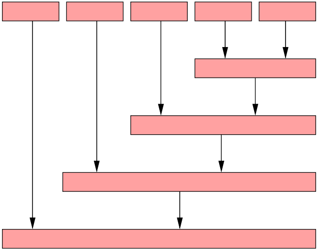
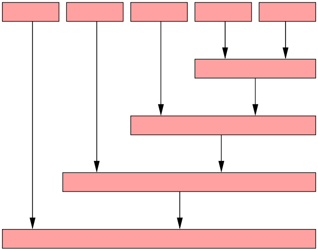


SAscan: parallel EM version

1. Divide text into blocks
   - small enough for RAM processing
2. Construct SA for each block in RAM
   - use internal memory pSAscan
3. Merge each block SA into full SA
   - key property: backward search needs rank data structure on BWT of left hand-size block
     $\Longrightarrow$ unbalanced merging
   - parallization: start backward search from multiple positions



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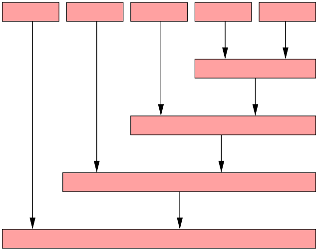

SAscan: parallel EM version

- $\Theta(n/M)$ blocks
- Time and I/O proportional to n^2/M
- Fastest SACA when

$$\frac{\text{text size}}{\text{RAM size}} < 80$$

(on 12-core machine)

- Lightweight w.r.t. disk space, uses 7.5n bytes
  - eSAIS: 28n

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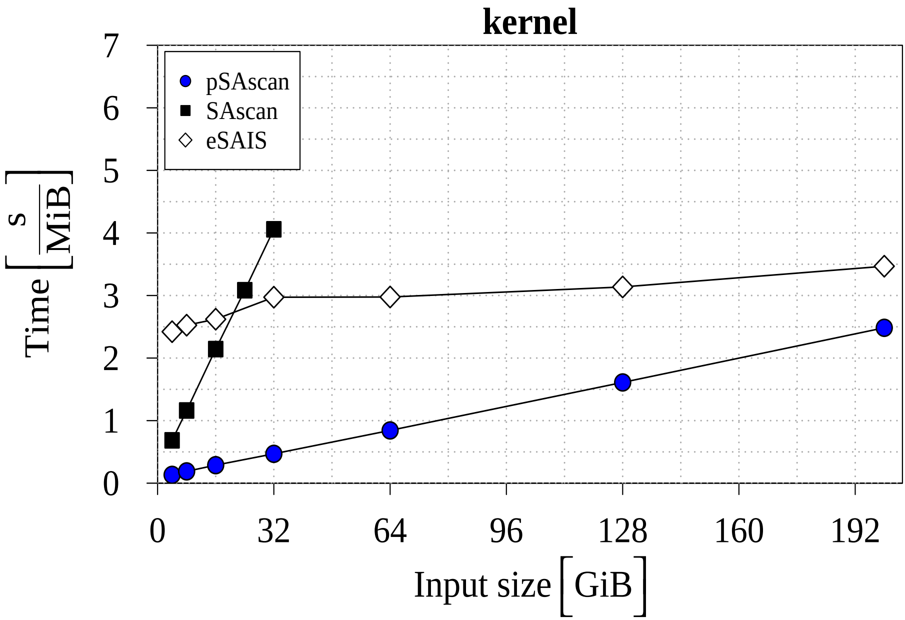
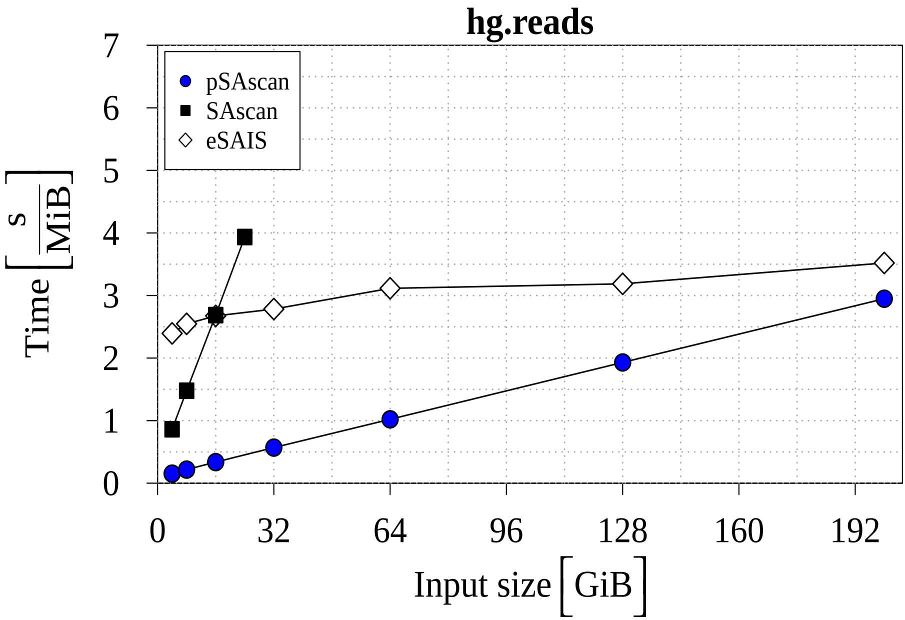
Experiments

(comparison of EM suffix array construction algorithms)



kernel
pSAscan
SAscan
eSAIS
Time [s/MiB]
0
1
2
3
4
5
6
7
0
32
64
96
128
160
192
Input size [GiB]



hg.reads
pSAscan
SAscan
eSAIS
Time [s/MiB]
0
1
2
3
4
5
6
7
0
32
64
96
128
160
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Input size [GiB]

- 200GiB prefix of `hg.reads`
  - Runtime

	3.5 GiB of RAM	120 GiB of RAM
eSAIS	8.3 days	4.1 days
pSAscan	7.0 days	0.5 days

  - Peak disk space usage

	3.5 GiB of RAM	120 GiB of RAM
eSAIS	4.6 TiB	4.6 TiB
pSAscan	1.4 TiB	1.4 TiB

  - I/O volume

	3.5 GiB of RAM	120 GiB of RAM
eSAIS	52.0 TiB	36.1 TiB
pSAscan	43.8 TiB	4.9 TiB

- Full instance (1TiB) of `hg.reads`, using 120GiB of RAM

	Runtime	Peak disk usage	I/O volume
pSAscan	8.1 days	7.3 TiB	48.3 TiB

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Concluding Remarks

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  - $2\times$ faster and $\sim 2.5\times$ less RAM than pDC3
- First external-memory parallel SACA
  - Fastest EM SACA when

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  - uses ~ 4 times less disk space than eSAIS

Possible further improvements

- smaller rank data structure
- distributed / GPU implementation?

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Thank you!

Code:
www.cs.helsinki.fi/group/pads/