Duration-Aware Alignment of Process Traces

Sen Yang

Moliang Zhou, Rachel Webman, JaeWon Yang, Aleksandra Sarcevic, Ivan Marsic and Randall S. Burd

Talk Overview

- Motivation of Research
- Duration-Aware Trace Alignment Algorithm
- Evaluation Criteria
- Case Studies

Previous Research: Expert Model

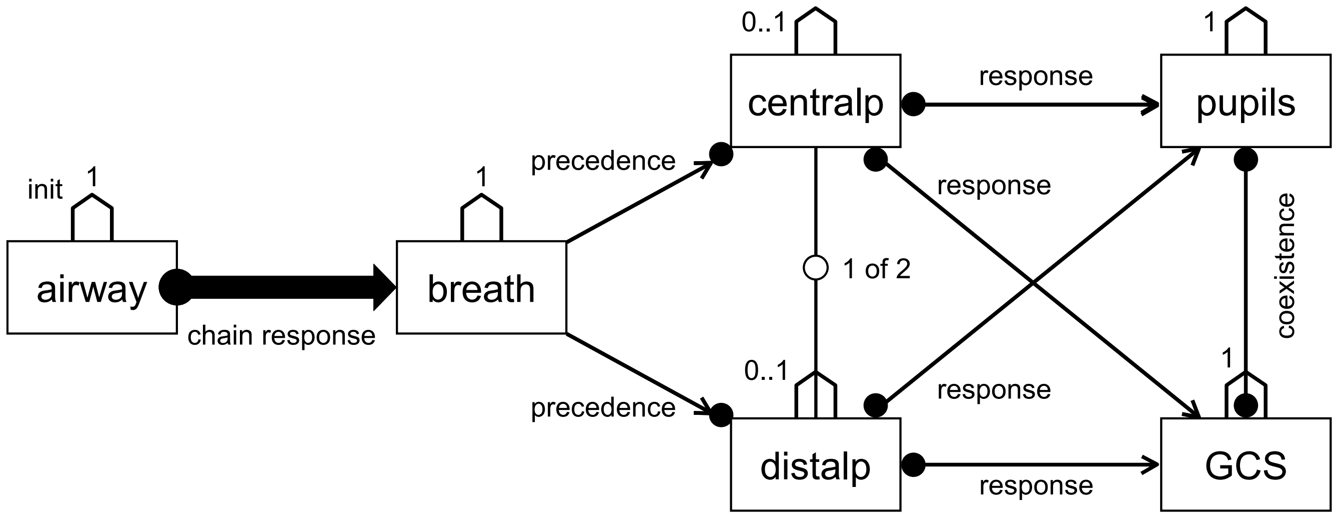


Figure: Expert-derived workflow model showing of essential activities by the bedside physician during the primary survey phase of ATLS (Advanced Trauma Life Support)

Previous Research: Trace Alignment

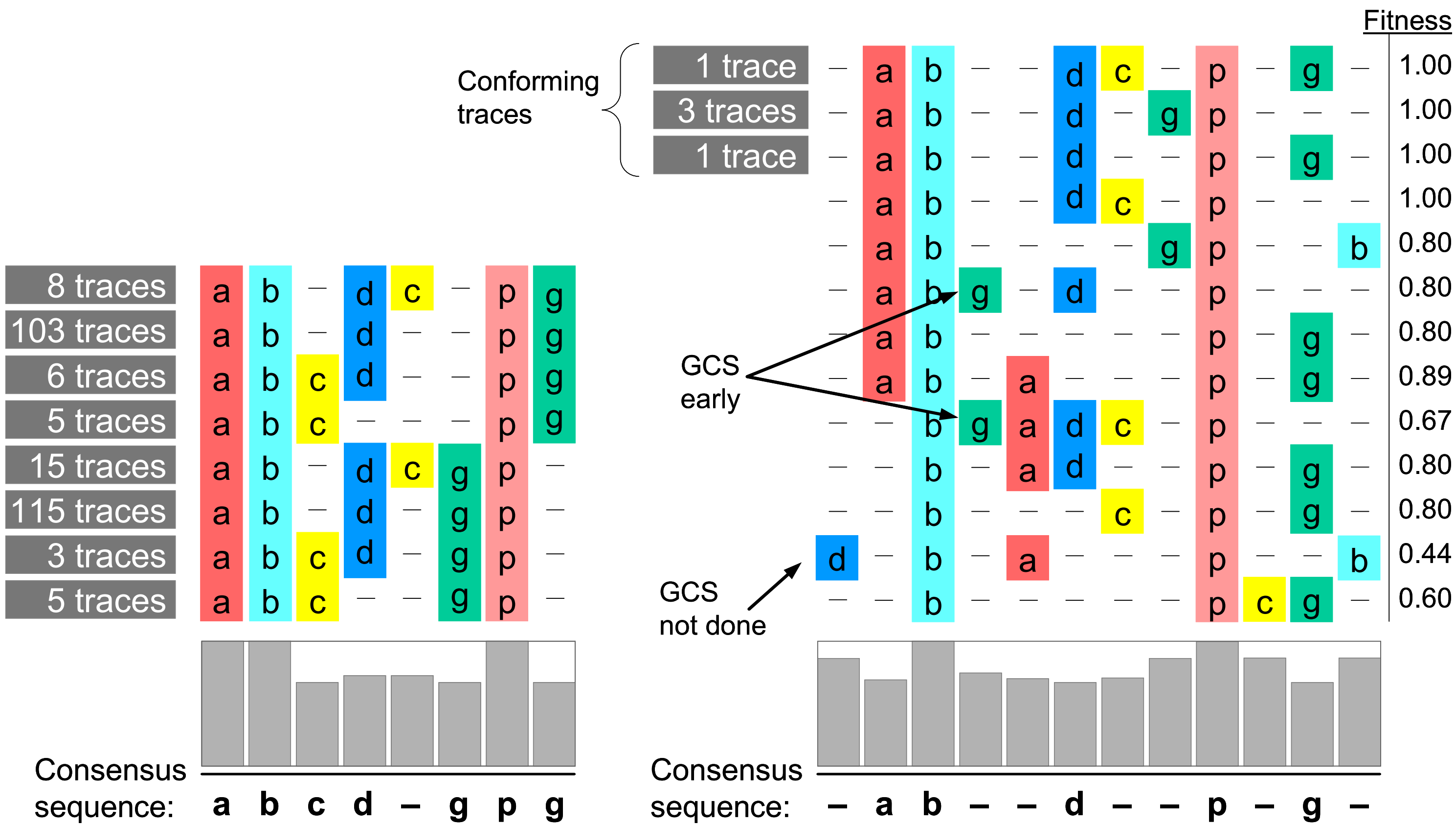


Figure: (left) Trace alignment of resuscitations conforming to the workflow model; (right) trace alignment of resuscitations in which evaluation of neurological status [GCS] was performed incorrectly.

Motivation of Duration-Aware Trace Alignment

Trace Alignment on medical processes:

- Helpful in visualizing the data
- Helpful in discovering deviations
  - similarities within a group of traces and to determine how a given trace differs from the well-established work practice
- Finding a sequential model
  - Consensus sequence can be seen as the backbone sequential model of the process

Limitation:

- Existing trace alignment approaches consider only the sequential order of activities and ignore activity duration.

Motivation of Duration-Aware Trace Alignment

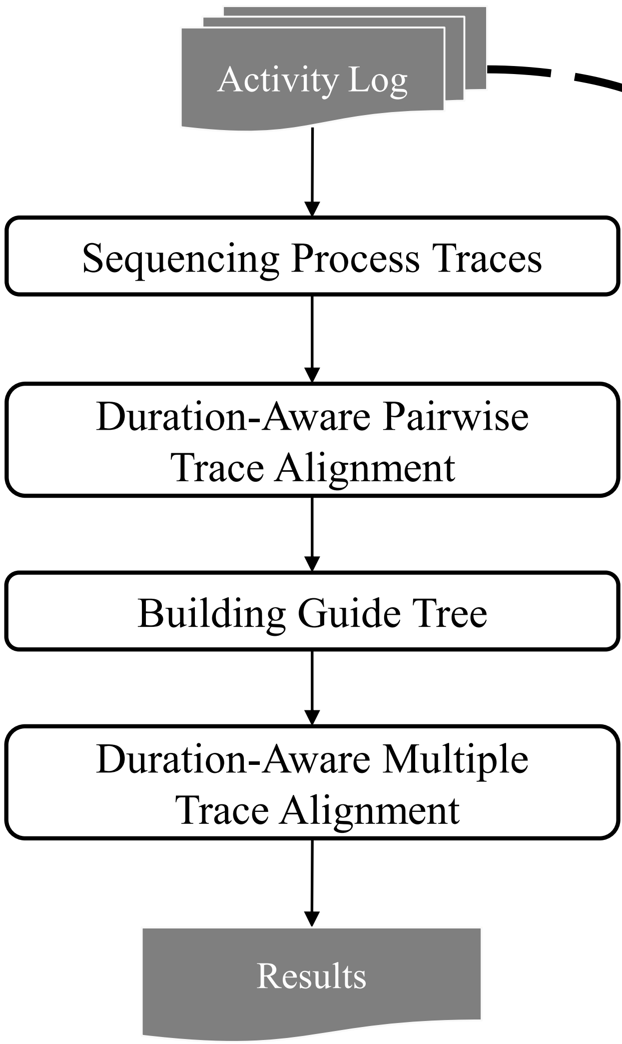
Activity duration is useful:

- Duration indicates activity similarity:
  - For example, consideration of duration helped understand that nurses routinely switch between tasks, spending less time on interrupted tasks that are later resumed
- Unusual durations indicate difficulties or atypical performance in the medical team operations

Question:

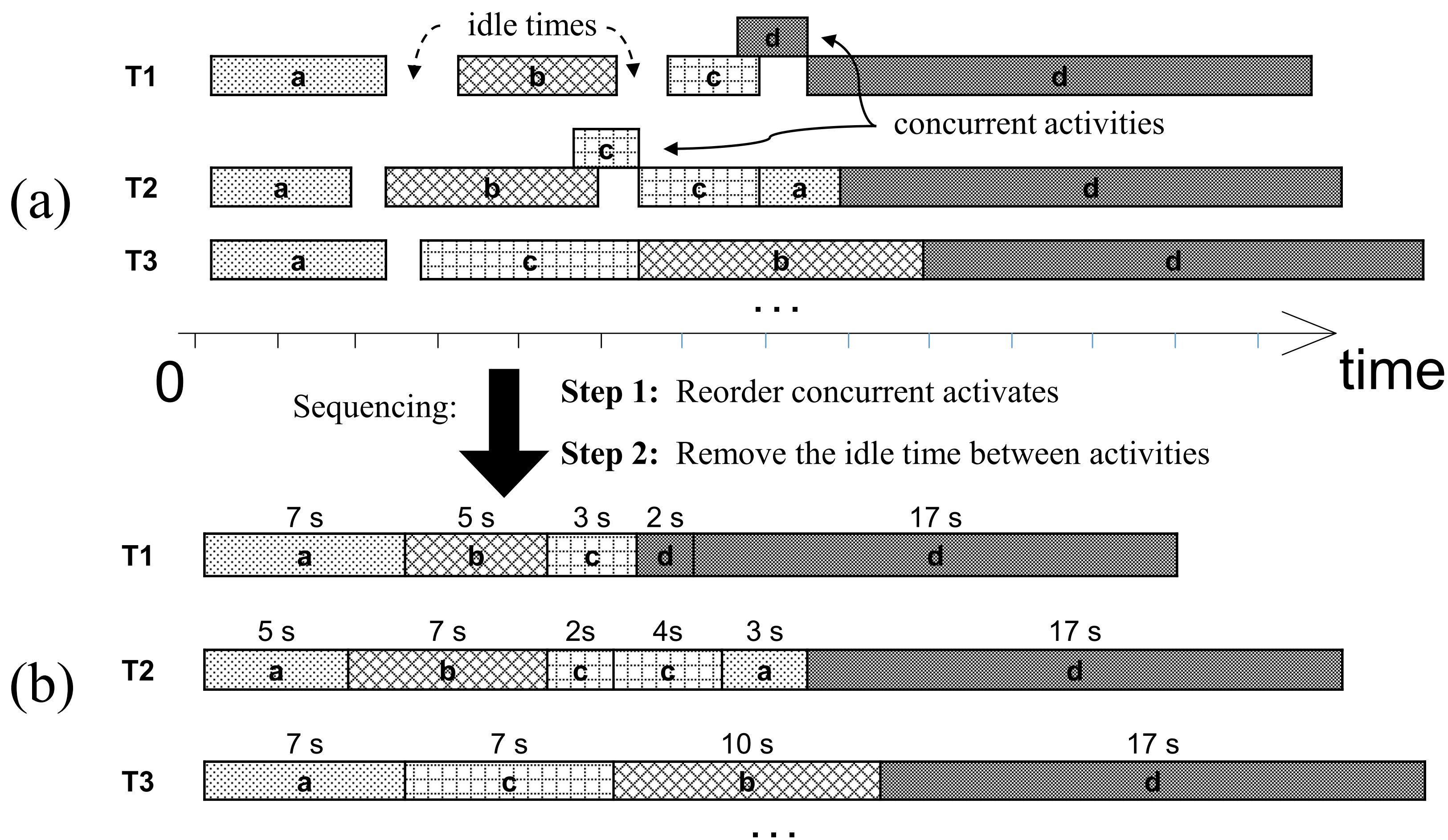
- How to include activity duration into consideration?
  - Dynamic Time Warping???

Duration-aware trace alignment flowchart

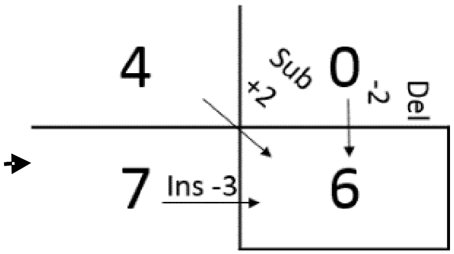


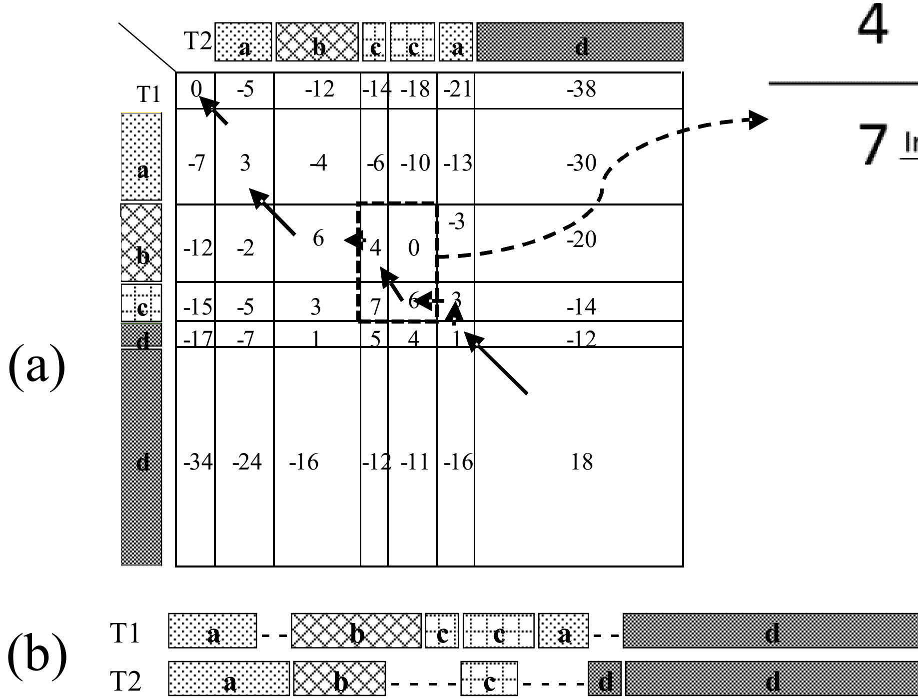
Study ID	Start Time	End Time	Activity
2014001	0:00:00	0:00:01	Patient Arrival
2014001	0:00:00	0:06:42	NRB
2014001	0:00:57	0:00:58	Airway Verbalized
2014001	0:01:10	0:01:36	Pre-Intubation Chest Auscultation
2014001	0:01:49	0:01:50	Breathing Verbalized
2014001	0:06:22	0:06:23	Decision to Intubate
2014001	0:06:44	0:10:07	BVM
2014001	0:07:53	0:08:13	RSI Sedative Meds
2014001	0:08:16	0:08:41	RSI Paralytic Meds

Sequencing of Process Traces



Pairwise Duration-Aware Trace Alignment





Scoring Scheme:

- S(a,b) = 1 Match
- S(a,b) = -1 Mismatch
- g = -1 Gap

$$F(i,j) = \max \begin{cases} F(i-1,j-1) + S\big(T_1(i),T_2(j)\big) * \; ddp\big(T_1(i),T_2(j)\big) & \text{Substitute} \\ F(i-1,j) + g * hdp(T_1(i)) & \text{Insert} \\ F(i,j-1) + g * vdp(T_2(j)) & \text{Delete} \end{cases}$$

Pairwise Duration-Aware Trace Alignment

Time Distortion Penalty Function:

$$hdp(T_1(i)) = \varphi\left(d(T_1(i))\right)$$

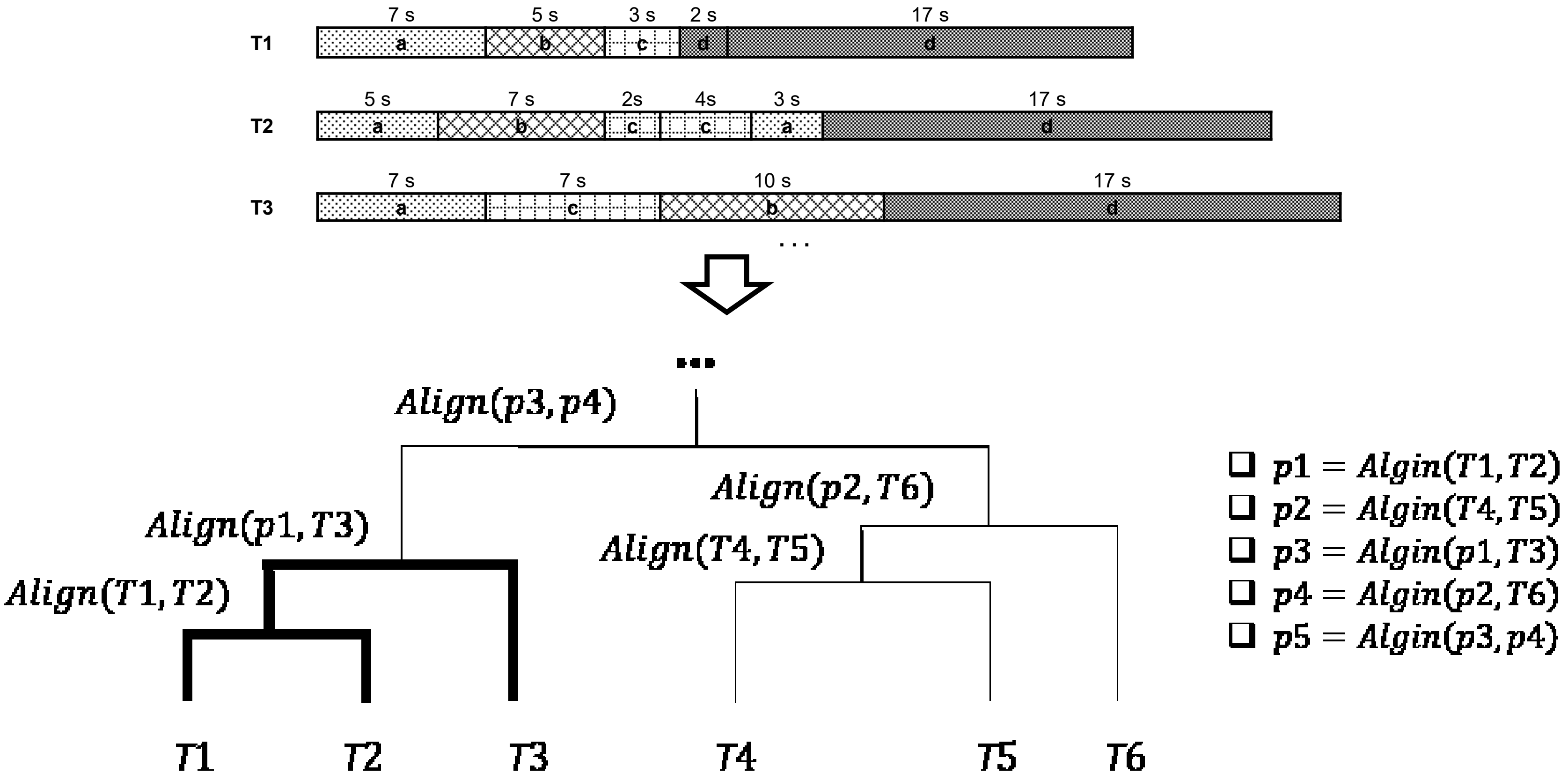
$$vdp(T_2(j)) = \varphi\left(d(T_2(j))\right)$$

$$ddp(T_1(i), T_2(j)) = \begin{cases} Min\left(\varphi\left(d(T_1(i))\right), \varphi\left(d(T_2(j))\right)\right) - \left|\varphi\left(d(T_1(i))\right) - \varphi\left(d(T_2(j))\right)\right|, & S(T_1(i), T_2(j)) \geq 0 \\ \varphi\left(d(T_1(i))\right) + \varphi\left(d(T_2(j))\right), & S(T_1(i), T_2(j)) < 0 \end{cases}$$

Time Weighting Function:

$$\begin{cases} \varphi_{Linear}(d(event)) = c * d(event) & \longleftarrow \text{Linear weighting} \\ \varphi_{Log}(d(event)) = \log_b(d(event)) & \longleftarrow \text{Logarithmic weighting} \end{cases}$$

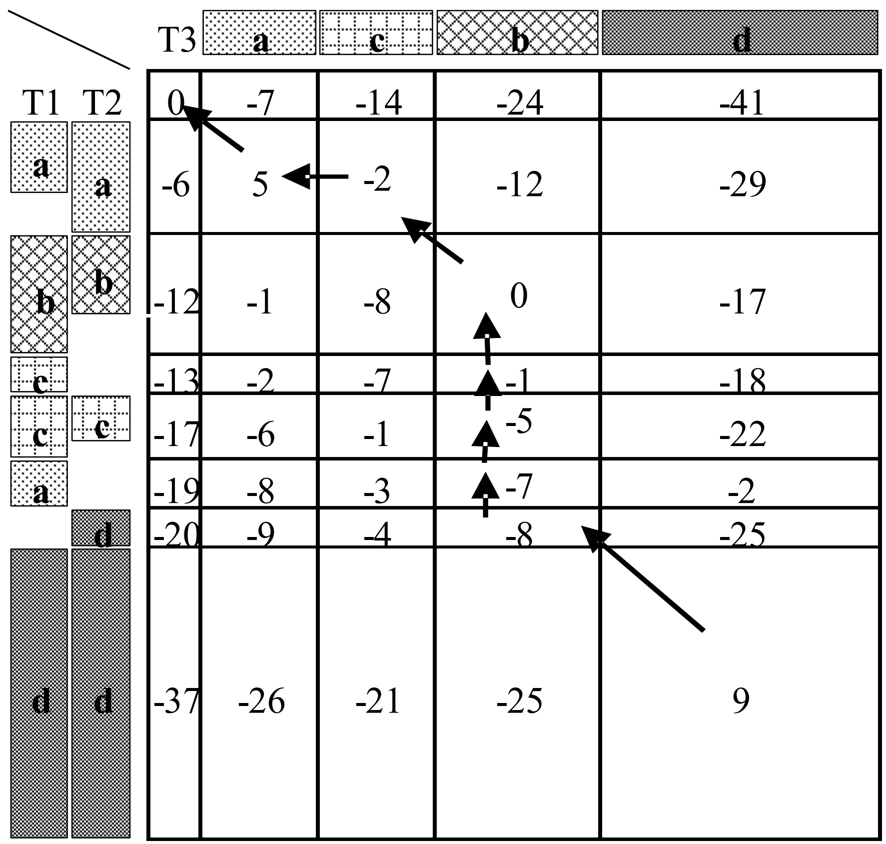
Guide Tree from Hierarchical Clustering



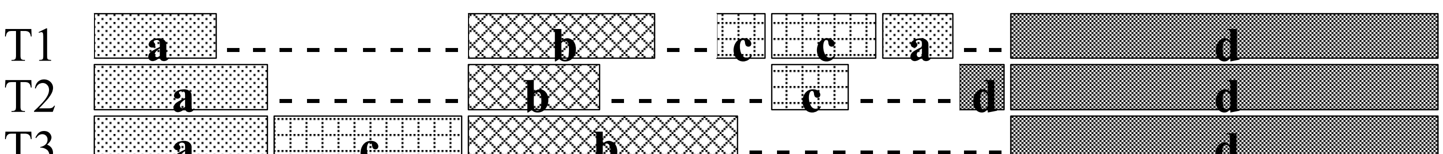
- Hierarchical tree grows based on Ward’s method
- Similarity of process traces based on Edit Distance (a.k.a. Levenshtein Distance [11]) or Duration-Aware Edit Distance

Multiple Duration-Aware Trace Alignment

(a)



(b)



Evaluation Criteria

- *Sum-of-pairs Score (SPS)*
- *Average Information Score*
- *Consensus Sequence (CS)*
- *Alignment Matrix Length*
- *Deviation Detection Ability*

Quantitative

Qualitative

Evaluation Criteria

1. *Sum-of-pairs Score (SPS)*

$$SPS = n/N$$

n : # of correctly aligned residue (activity) pairs in the test alignment

N: total # of residue (activity) pairs in the reference alignment

Example:

Trace 1:	A	B	–
Trace 2:	A	B	–
Trace 3:	–	B	A

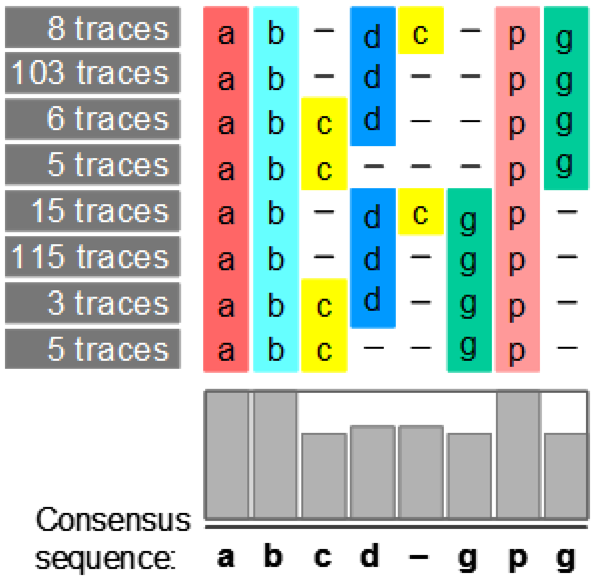
Reference Alignment

Trace 1:	–	A	B
Trace 2:	–	A	B
Trace 3:	B	A	–

Test Alignment

SPS = 2/8 = 0.25

Evaluation Criteria



2. *Average Information Score (IS):*

$$IS_i = \left(1 - \frac{E}{E_{max}}\right)$$

where $E_{max} = \log_2(|\mathbb{A}| + 1)$; $E = \sum_{a \in \mathbb{A} \cup \{-\}} -p_a \log_2(p_a)$

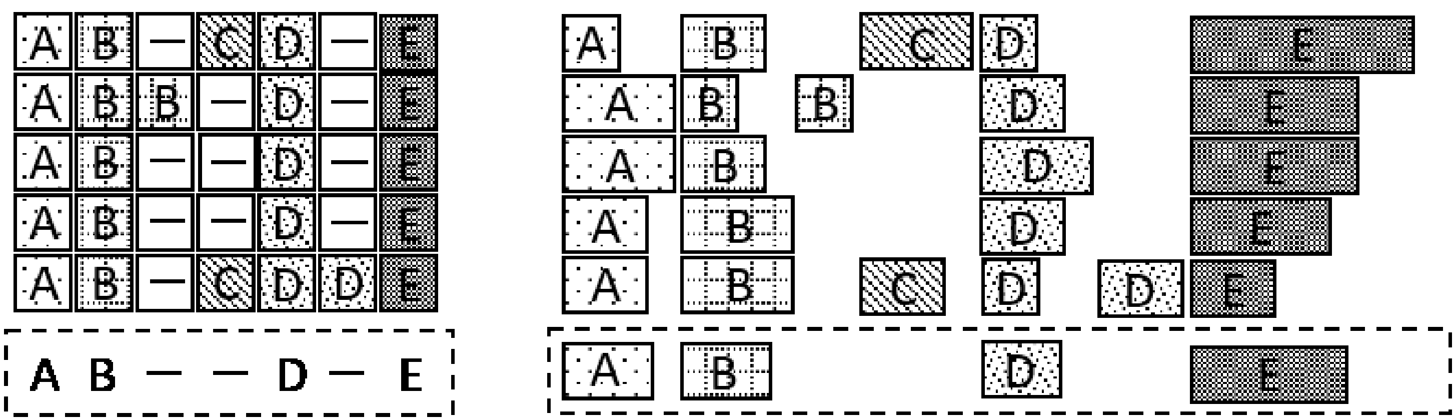
$$Avg.IS = \left(\sum IS_i\right) / L$$

L is alignment matrix length, i.e., # columns in alignment matrix

Evaluation Criteria

3. Consensus Sequence (CS):

The consensus sequence denotes a sequence of the most frequent activity found in each column of the alignment matrix.



(a) (b)

Evaluation Criteria

4. *Alignment Matrix Length:*

   Shorter matrix length is preferred. Longer alignment matrix may indicate that unnecessary gaps are included into the alignment.

Example:

Trace 1:	A	B	–
Trace 2:	A	B	–
Trace 3:	–	B	A

Dense Matrix

Trace 1:	–	A	B	–
Trace 2:	–	A	B	–
Trace 3:	B	–	–	A

Sparse Matrix

Case Study 1: Trauma Resuscitation Process

- Data Coded based on the videos in CNMC
- 33 cases with a total 244 activities of 8 different types
  (Question: small data?)

Algorithm: / Metrics:	Duration-Aware (linear)	Duration-Aware (logarithmic)	Context-based
Sum-of-pairs Score	0.617	**0.807**	0.731
Avg. Information Score	**0.870**	0.863	0.848
No. Non-gap Activities in CS	6	**7**	6
Alignment Matrix Length	49	39	**36**

RUTGERS

Reference Alignment

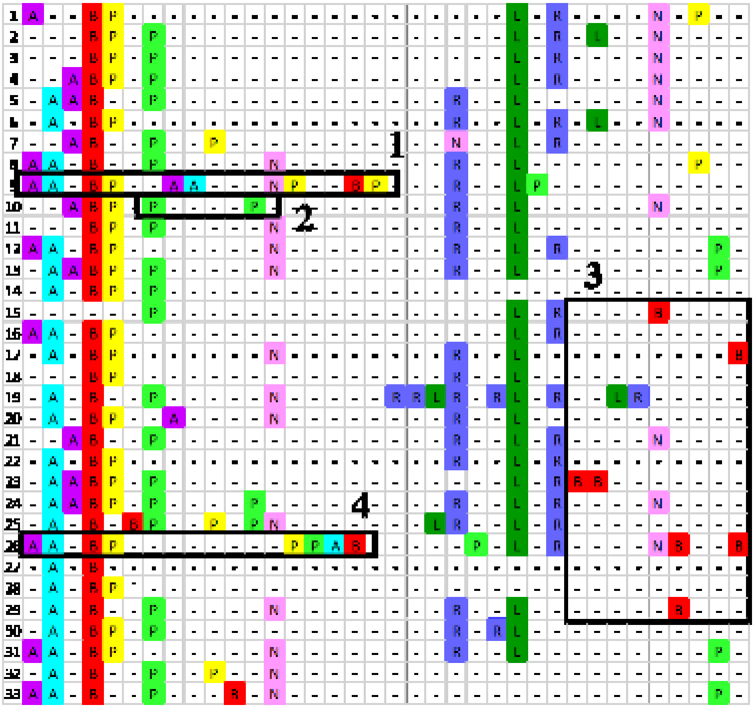
1	-	-	-	-	-	-	A	-	-	-	-	B	-	P	-	-	-	-	-	-	-	L	R	-	-	-	-	-	N	-	-	-	P	-
2	-	-	-	-	-	-	-	-	-	-	-	B	-	P	-	P	-	-	-	-	-	L	R	-	L	-	-	-	N	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	B	-	P	-	P	-	-	-	-	-	L	R	-	-	-	-	-	N	-	-	-	-	-
4	-	-	-	-	-	-	A	-	-	-	-	B	-	P	-	P	-	-	-	-	-	L	R	-	-	-	-	-	N	-	-	-	-	-
5	-	-	-	-	-	-	A	A	-	-	-	B	-	-	-	P	-	-	-	R	-	L	-	-	-	-	-	-	N	-	-	-	-	-
6	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	-	-	-	-	R	-	L	R	-	L	-	-	-	N	-	-	-	-	-
7	-	-	-	-	-	-	A	-	-	-	-	B	P	P	-	-	-	-	N	-	-	L	R	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	A	A	-	-	-	B	-	-	-	P	-	-	N	R	-	L	-	-	-	-	-	-	-	-	-	-	-	P
9	A	A	B	P	-	-	A	A	N	P	-	B	-	P	-	-	-	-	-	R	-	L	-	-	-	-	-	-	-	P	-	-	-	-
10	-	-	-	-	-	-	A	-	-	-	-	B	-	P	P	P	-	-	-	R	-	L	-	-	-	-	-	-	N	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	B	-	P	-	P	-	-	N	R	-	L	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	A	A	-	-	-	B	-	P	-	-	-	-	N	R	-	L	R	-	-	-	-	-	-	P	-	-	-	-
13	-	-	-	-	-	-	A	A	-	-	-	B	-	P	-	P	-	-	N	R	-	L	-	-	-	-	-	-	-	P	-	-	-	-
14	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P	-	-	-	-	-	L	R	-	-	-	-	-	-	-	B	-	-	-
16	-	-	-	-	-	-	A	A	-	-	-	B	-	P	-	-	-	-	-	-	-	L	R	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	-	-	-	N	R	-	L	-	-	-	-	-	-	-	-	B	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	B	-	P	-	-	-	-	-	R	-	L	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	A	-	-	-	B	-	-	-	P	-	-	N	R	R	L	R	R	L	R	L	R	-	-	-	-	-	-
20	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	-	A	-	N	R	-	L	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	A	-	-	-	-	B	-	-	-	P	-	-	-	R	-	L	R	-	-	-	-	-	N	-	-	-	-	-
22	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	-	-	-	-	R	-	L	R	-	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	A	A	-	-	-	B	-	P	-	P	-	-	-	-	-	L	R	-	-	-	-	-	-	-	B	B	-	-
24	-	-	-	-	-	-	A	A	-	-	-	B	-	P	P	P	-	-	-	R	-	L	R	-	-	-	-	-	N	-	-	-	-	-
25	-	-	-	-	-	-	-	A	-	-	B	B	P	P	-	P	-	-	N	-	-	L	R	-	L	R	-	-	-	-	-	-	-	-
26	A	A	B	P	P	P	-	A	-	-	-	B	-	-	-	P	-	-	-	-	-	L	R	-	-	-	-	-	N	-	B	B	-	-
27	-	-	-	-	-	-	-	A	-	-	-	B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	A	-	-	-	B	-	-	-	P	-	-	N	R	-	L	-	-	-	-	-	-	-	-	B	-	-	-
30	-	-	-	-	-	-	-	A	-	-	-	B	-	P	-	P	-	-	-	R	-	-	R	-	L	-	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	A	A	-	-	-	B	-	P	-	-	-	-	N	R	-	L	-	-	-	-	-	-	-	P	-	-	-	-
32	-	-	-	-	-	-	-	A	-	-	-	B	P	P	-	-	-	-	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33	-	-	-	-	-	-	A	A	-	-	-	B	-	-	-	P	-	B	N	-	-	-	-	-	-	-	-	-	-	P	-	-	-	-

- ❑ The reference alignment functions as a ground truth.
- ❑ Created manually by medical experts.

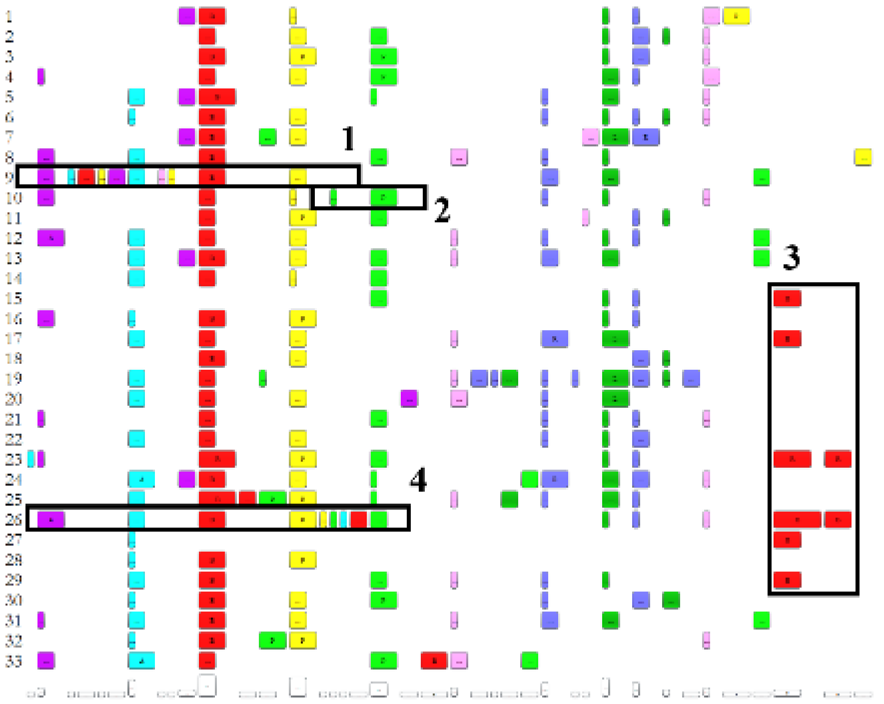
P	Pulse Check - Upper Extremity	B	Breath Sounds Check	P	Pulse Check - Lower Extremity
L	Left Pupil Check	R	Right Pupil Check	N	Neurologic assessment
A	Airway Assessment Verbal	A	Airway Assessment Visual		

Context-Aware vs. Duration-Aware Alignment

Context-Aware



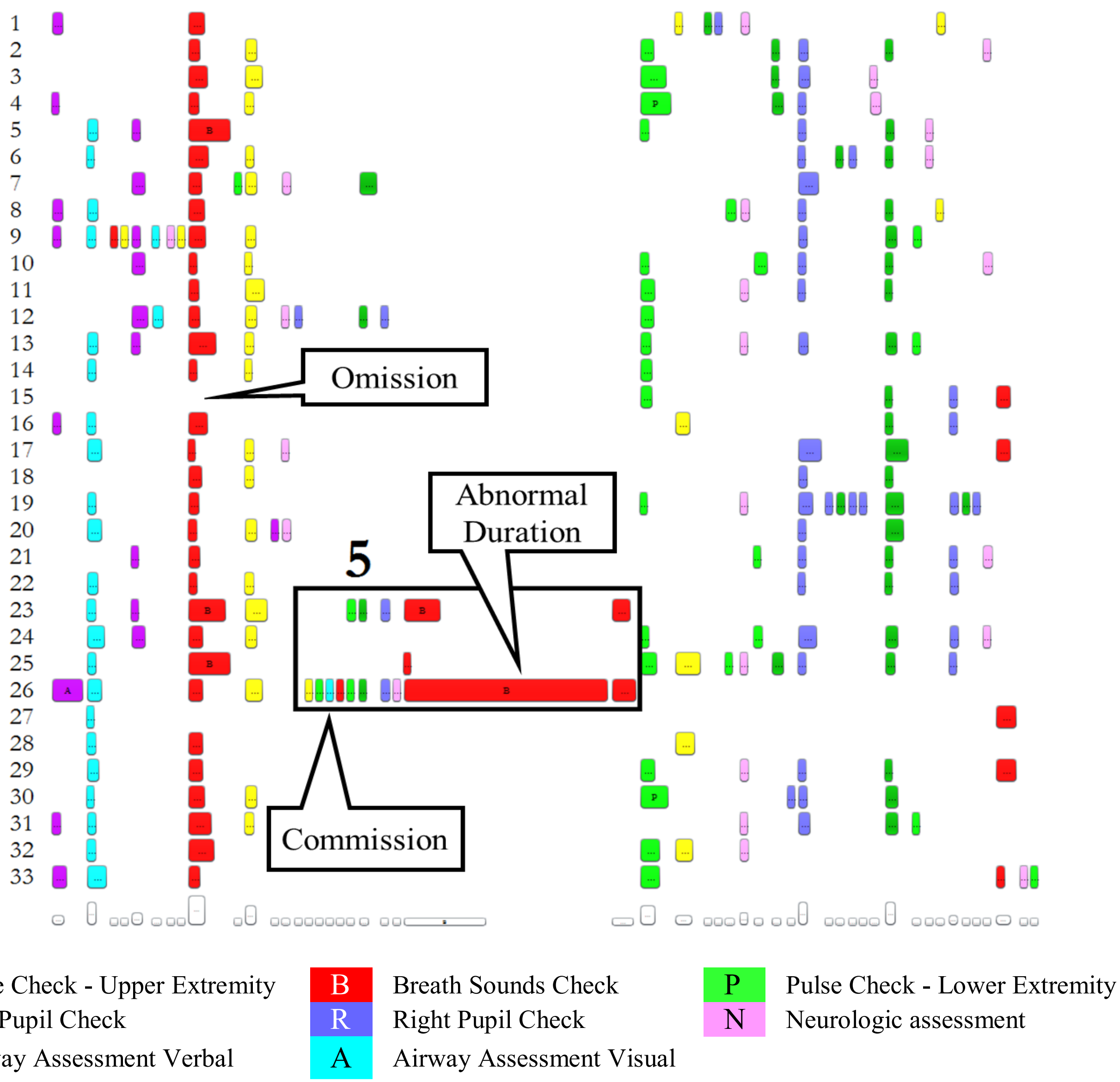
Duration-Aware (Logarithmic Weighting)



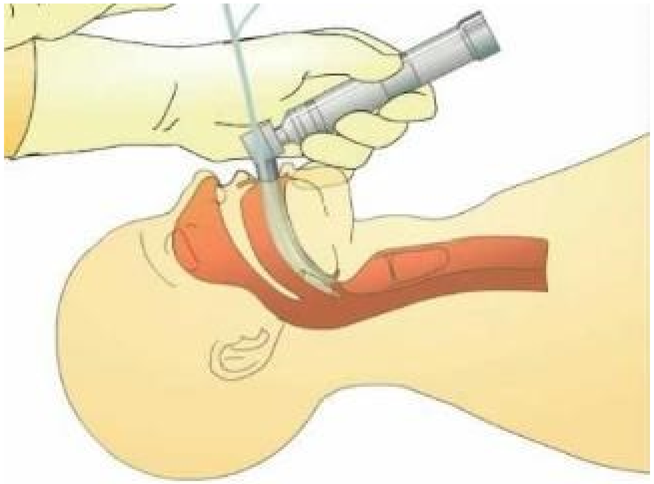
P	Pulse Check - Upper Extremity	B	Breath Sounds Check	P	Pulse Check - Lower Extremity
L	Left Pupil Check	R	Right Pupil Check	N	Neurologic assessment
A	Airway Assessment Verbal	A	Airway Assessment Visual		

Rutgers

Duration-Aware (Linear Weighting)



Case Study 2: Endotracheal Intubation Process

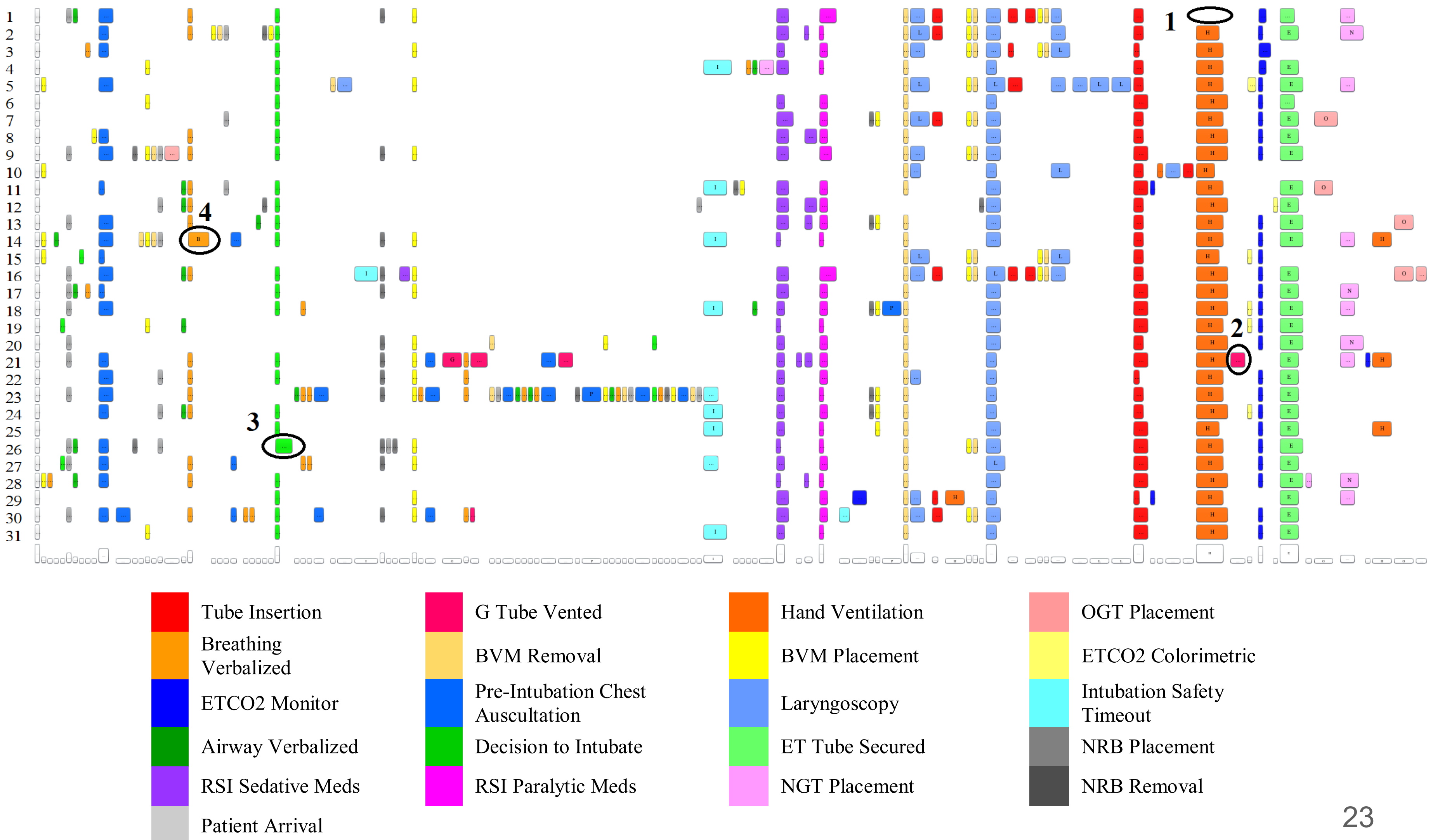


- Data Coded based on the videos in CNMC
- 31 cases with a total 602 activities of 21 different types

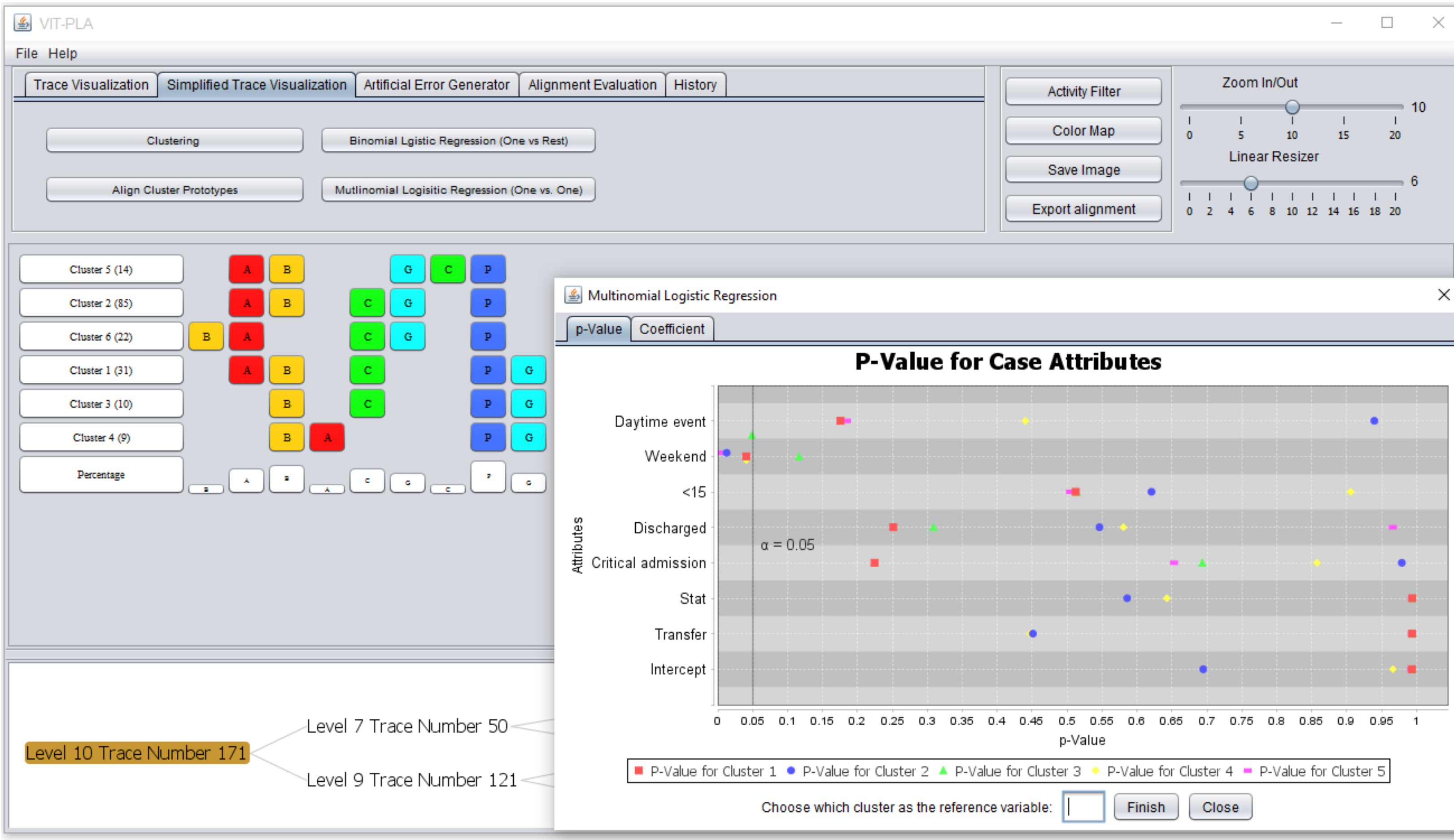
Algorithm: / Metrics:	Duration-Aware (linear)	Duration-Aware (logarithmic)	Context-based
Sum-of-pairs Score	0.731	**0.843**	0.721
Avg. Information Score	0.918	**0.919**	0.899
No. Non-gap Activities in CS	10	12	**13**
Alignment Matrix Length	134	119	**115**

Figure Source: https://www.youtube.com/watch?v=-71COfjNIz0

Duration-Aware Alignment (Logarithmic)



Implementation



Scalability

$O(n^2 l^2 + n^3)$ → Trace Clustering (i.e., Guide Tree)
$O(n^2 L + nL^2)$ → Trace Alignment
Where:
- n: trace number
- l: average trace length
- L: average length of traces or profiles taken into alignment

Table. Computation Time. The notation $\boldsymbol{t} \pm \boldsymbol{\delta}$ denotes the computation time where t is the mean value over 20 difference runs and $\boldsymbol{\delta}$ is the standard deviation

Log	No. traces	Total activities	Guide Tree (ms)	Progressive Alignment (ms)	Visualization (ms)
Intubation	31	605	15 ± 1	10 ± 1	4 ± 1
Trauma Resuscitation	33	4482	105 ± 5	242 ± 16	19 ± 2
Artificial Data	1000	52179	12493 ± 227	12353 ± 749	591 ± 51

Conclusion

1) A novel trace alignment algorithm that is duration-aware
2) A set of criteria to quantify trace alignment algorithm performance
3) Case studies showed our alignment algorithm achieved better alignment accuracy and provided more insights into deviations
4) Algorithm implemented into a JAVA APP

Limitations

1) Information lost in the “Process Trace Sequencing” step
2) Algorithm needs activity durations as input

Thank you

QUESTION?

Have workflow data that needs visualization and analysis?

Sen Yang sy358@scarletmail.rutgers.edu