Inference of alternative splicing from RNA-Seq data with probabilistic splice graphs

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Overview

• Part I - Alternative splicing and the challenges it poses

• Part II - A solution: *Probabilistic Splice Graphs (PSGs)*

• Part III - Evaluating PSG methodology
Alternative splicing

pre-mRNA

splicing

alternatively spliced mRNAs

translation

protein isoforms
Classes of alternative splicing events

- Exon skipping
- Mutually exclusive exons
- Alternative 5' donor sites
- Alternative 3' acceptor sites
- Intron retention
Complication 1: De novo transcriptome assembly

- RNA-Seq reads/fragments are relatively short
- Often insufficient to reconstruct full-length isoforms in the presence of alternative splicing
- Transcriptome assemblies perhaps best left in “graph” form
  - De Bruijn graph
  - String graphs

Graph constructed by the “Butterfly” module of Trinity (Grabherr et al. 2011)
Complication 2: Non-identifiability of full-length isoform models

Lacroix et al. 2008; Hiller et al. 2009
Complication 3: Combinatorial explosion of distinct isoforms

- Combinatorial explosion of the number of possible isoforms for each gene

- Insufficient data to accurately estimate abundances of thousands of isoforms

Drosophila Dscam: more than 38,000 possible isoforms
(Schmucker et al., 2000)
Overview

• Part I - Alternative splicing and the challenges it poses

• Part II - A solution: *Probabilistic Splice Graphs (PSGs)*

• Part III - Evaluating PSG methodology
Splice Graphs

• Heber et al. 2002

• Compact **data structure** for representing the possible isoforms of a gene
Splice Graphs with EST and RNA-Seq data

- Xing et al. 2006
  - EM algorithm for estimating abundances of all possible isoforms given splice graph and EST data

- Montgomery et al. 2010, Singh et al. 2011
  - Graph flow-based methods for quantification/differential splicing given RNA-Seq data

- Rogers et al. 2012
  - SpliceGrapher: construct splice graph structure given RNA-Seq data
Probabilistic Splice Graphs

- Jenkins et al. 2006

- Compact **probabilistic model** representing isoform frequencies in terms of frequencies of individual splice events

- Originally used by Jenkins et al. for EST analysis

![Diagram of probabilistic splice graphs with probabilities 0.8, 0.4, 0.2, 0.6, 0.32, 0.48, 0.08, and 0.12]
Probabilistic Splice Graph Complexity

known isoforms
“line graph”
“exon graph”
“higher-order exon graph”
“unfactorized graph”
Advantages of PSGs

- **Compact** description of the possible isoforms of a gene
  - Models the frequencies of potentially exponentially many isoforms with a *polynomial* number of parameters
  - Models *dependence or independence* of splice events
  - The parameters of a PSG are more often *identifiable* than a model that has a parameter for every possible isoform
  - Splice graphs are *naturally-produced structures* from transcriptome assemblers
PSGs are alternative “parsimonious” models

- Other methods find smallest set of isoform structures that explain the data

  - Cufflinks (Trapnell et al., 2010)
  
  - IsoLasso (Li et al., 2011)
  
  - NSMAP (Xia et al., 2011)
  
  - SLIDE (Li et al., 2011)

- PSG models are another form of parsimonious model

  - Minimize the number of splice event parameters
  
  - Assumption of independence between splice events
Our contributions

• Application of PSGs to RNA-Seq data

  • Combined model of PSG with RNA-Seq generative model

  • Efficient PSG parameter estimation with EM and dynamic programming

  • Identifiability proofs for PSG with RNA-Seq data

  • Differential processing (splicing) tests

The PSG parameter inference task

• Given: RNA-Seq reads and a PSG structure

CCTTCNCACTTCGTTCCTCAC
TTTTTNCAAGGTTTTTTCTTGTG
GAACANTCCAACGCTTTGGGTA
GGAAANAAGACCCCTGGTGGAC
CCCGGNATCCGGCTGGGACAA
GCAGCATATTGATAGATAACT
CTAGCTACGTACGTACGCGG
CATCTAGCATCGCGTTGCGTT

• Do: Estimate the (ML or MAP) parameters for the model
A model of RNA-Seq from PSGs

• RSEM model extended to probabilistic splice graphs
  • fragment length distribution, quality scores, read mapping ambiguity
  • Dynamic programming algorithms → polynomial time inference for genes with an exponential number of isoforms

Probability of including vertex \( j \) given that vertex \( i \) was in transcript

\[
f(i, j) = \sum_{s: s_1, s_{|s|} = j} w(s) = \begin{cases} 
1 & i = j \\
\sum_k \alpha_{k,j} f(i, k) & i \neq j
\end{cases}
\]

Expected prefix length

\[
d_p(i) = \ell_i + \frac{1}{f(0, i)} \sum_j f(0, j) \alpha_{i,j} d_p(j)
\]

Expected suffix length

\[
d_q(i) = \ell_i + \sum_j \alpha_{i,j} d_q(j)
\]
EM for PSG parameter estimation

- **E-step:** compute the expectation of the number of times edge \((i,j)\) is used

\[
E[Z_{n(i,j)}] = \frac{\sum_{(b,s) \in \mathcal{E}(r)} g(s, i, j)}{\sum_{(b,s) \in \mathcal{E}(r)} g(s)}
\]

\[
g(s) = f(0, s_1)w(s)
\]

\[
g(s, i, j) = \begin{cases} 
  f(0, s_1)w(s) & (i, j) \in s \\
  f(0, i)\alpha_{ij}f(j, s_1)w(s) & \text{if } \exists \text{ path from } v_j \text{ to } s_1 \\
  f(0, s_1)w(s)f(s_{|s|}, i)\alpha_{ij} & \text{if } \exists \text{ path from } s_{|s|} \text{ to } v_i \\
  0 & \text{otherwise}
\end{cases}
\]

- **M-step:** maximize the completely-observed likelihood given the edge counts

\[
\alpha_{ij} = \frac{z_{ij}}{\sum_k (z_{jk} + z_{ik})}
\]
Identifiability of PSGs with RNA-Seq data

- Identifiability: \( P(D|M, \theta) = P(D|M, \theta'), \forall D \Leftrightarrow \theta = \theta' \)

- Proposition: If for all edges \((u, v)\), there exists a read that is uniquely derived from that edge, or \(v\) has indegree 1 and there exists a read that is uniquely derived from \(v\), then the PSG is identifiable.
The differential processing (DP) task

- Given: RNA-Seq reads from two conditions and a PSG structure

condition 1

CCTTCNCACTTCGTTCAC
TTTTTNCAAGCTTTTTTCTTG
GAACANTCCAACGCTTTGCTGA
GGAGAANAAGACCCTGTGGAGC
CCCGGNGATCCGCTGGAACAA
GCAGCATATTGATAAGATAACT
CTAGCTACGCTACGCTGATCG
CATCTAGCATCGCTGTTGCGTT

condition 2

CATATCGTCGTAGCTAGTACG
CCACACTAGGTACGTGCGCA
TCGACGCTACCGCCTCGCAGC
ACTAGTACGTACGTTAGTACGT
GGATGCTCACAGGCTATCGG
GCATTCGGAAGCTCATCGA
AACCATCGGAAGGCCGTTTAA
CAGCTAGGCCTAGCCGCTTTT
CATGCTAGCGCGATCGCGTAG
GCATCGACTCGCGACCGATCC
ACGCATCGACTCGCGCATCGC

- Do: Determine if the processing frequencies are different

\[ \alpha_1 = \alpha'_1 \text{ and } \alpha_2 = \alpha'_2 ? \]
\[ \alpha_1 = \alpha'_1 \text{ or } \alpha_2 = \alpha'_2 ? \]
Our approach to the differential processing (DP) task

• Simple likelihood ratio tests with PSG model

• Test for null hypothesis that all frequencies are the same

\[
\text{LR} = \frac{P(R^1|\delta^1)P(R^2|\delta^2)}{P(R^1 \cup R^2|\delta^{12})}
\]

• Test for null hypothesis that frequencies of edges out of one vertex \((i)\) are the same

\[
\text{LR} = \frac{P(R^1|\hat{\alpha}^1)P(R^2|\hat{\alpha}^2)}{P(R^1, R^2|\hat{\alpha}^1_i, \hat{\alpha}^2_i, \hat{\alpha}_{i}^{12})}
\]
Overview

• Part I - The problem

• Part II - A solution: *Probabilistic Splice Graphs (PSGs)*

• Part III - Evaluating PSG methodology
Efficient inference for highly-spliced genes

- DSCAM running time test
  - 23,976 isoforms
  - 184 read pairs from a modENCODE sample

<table>
<thead>
<tr>
<th>Method</th>
<th>RSEM</th>
<th>Cufflinks</th>
<th>PSG EM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time</td>
<td>Not possible</td>
<td>&gt; 6 hours</td>
<td>&lt; 3 seconds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt; 90 GB RAM)</td>
<td></td>
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</table>
A simple method for comparison

• The Junction-Read (JR) method

• Keep only reads that align to the splice junctions (edges in the PSG)

• Throws away data, but is very robust to model assumption violations
Convergence with simulated data
Comparisons on real data

• Require notion of “distance” between estimates from different methods

• Our distance measure:
  
  • per vertex
  
  • maximum difference between probability estimates on out-edges of vertex (L-∞ norm)

\[
distance_v(A, B) = \max(|0.6 - 0.2|, |0.5 - 0.3|, |0.3 - 0.1|) = 0.4
\]
How close are the estimates from JR and EM on real data?

Vertices from 88 most abundant (> 5000 reads) alternatively-spliced genes in a modENCODE fly data set.
Convergence of estimates on real data
Comparing PSGs of different complexity

- Same set of fly data
- Estimated with three classes of PSG: line, exon, full-length
- Compared estimates to those from JR (gold-standard)
- No statistically-significant difference between exon and full-length graph estimates
Summary of Junction-Read comparison results

• Estimates using PSG models are generally close to those from the simplistic JR-method
  
  • ⇒ PSG model assumptions appear to be reasonable

• PSG estimates converge more quickly as the data set increases in size
  
  • ⇒ Our EM estimation procedure uses information from all reads, not just those that span splice junctions

• Exon-graph estimates as good as those using traditional full-length isoform models
  
  • ⇒ Independence assumptions of exon graphs appear to be reasonable
Differential processing detection

DP Accuracy on real data

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>PSG</th>
<th>FDM</th>
<th>Cuffdiff</th>
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Differential processing detection

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<th>Method</th>
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<td>B Rep 1</td>
<td>B Rep 2</td>
<td>148</td>
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</tbody>
</table>

Simulations based on two ENCODE cell lines, 10% of genes selected to be DP
Next steps for modeling RNA-Seq with PSGs

- Graph construction
- Exon discovery
- Splice junction discovery
- Model selection
- Learning dependencies between splice events
Summary

- **Alternative splicing** is a significant complication in RNA-Seq analysis.

- **Probabilistic Splice Graphs** enable identifiable models for alternatively spliced genes with efficient inference algorithms.

- **Differential processing** (splicing) tests with PSG models look promising.