RETIMING

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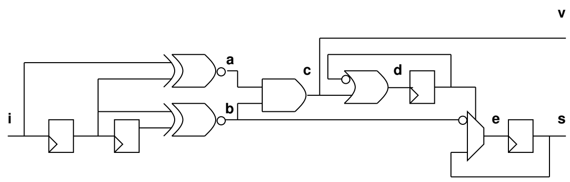
Outline

- Structural optimization methods.
- Retiming.
  - Modeling.
  - Retiming for minimum delay.
  - Retiming for minimum area.

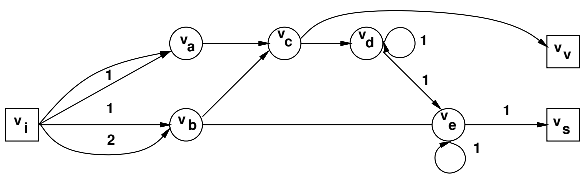
Synchronous Logic Network

- Synchronous logic network:
  - Variables.
  - Boolean equations.
  - Synchronous delay annotation.
- Synchronous network graph:
  - Vertices ↔ equations ↔ I/O , gates.
  - Edges ↔ dependencies ↔ nets.
  - Weights ↔ synch. delays ↔ registers.

Synchronous Logic Network Example



(a)



(b)

Example

$$\begin{aligned}
a^{(n)} &= i^{(n)} \overline{\oplus} i^{(n-1)} \\
b^{(n)} &= i^{(n-1)} \overline{\oplus} i^{(n-2)} \\
c^{(n)} &= a^{(n)} b^{(n)} \\
d^{(n)} &= c^{(n)} + d'^{(n-1)} \\
e^{(n)} &= d^{(n)} e^{(n-1)} + d'^{(n)} b'^{(n)} \\
v^{(n)} &= c^{(n)} \\
s^{(n)} &= e^{(n-1)}
\end{aligned}$$

$$\begin{aligned}
a &= i \overline{\oplus} i@1 \\
b &= i@1 \overline{\oplus} i@2 \\
c &= a\ b \\
d &= c + d@1' \\
e &= d\ e@1 + d'\ b' \\
v &= c \\
s &= e@1
\end{aligned}$$

Synchronous Logic Circuit Modeling

- State-based model:
  - Transition diagrams or tables.
  - *Explicit* notion of *state*.
  - *Implicit* notion of *area* and *delay*.
- Structural model:
  - Synchronous logic network.
  - *Implicit* notion of *state*.
  - *Explicit* notion of *area* and *delay*.

Approaches to synchronous logic optimization

- Optimize combinational logic only.
- Optimize register position only:
  - *Retiming.*
- Optimize overall circuit:
  - *Peripheral retiming.*
  - *Synchronous transformations:*
    - Algebraic.
    - Boolean.

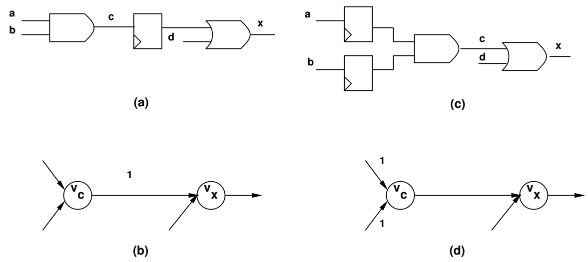
Separate registers from combinational logic

- Optimize combinational logic by transformations:
  - Modify equations.
  - Modify graph structure.
- Connect registers back into the network:
  - Good heuristic.
  - Limited by the partitioning strategy.

Retiming

- Move register position.
- Do not modify combinational logic.
- Preserve network structure:
  - Modify weights.
  - Do not modify graph structure.

Example



Retiming

- Global optimization technique [Leiserson].
- Changes register positions:
  - affects *area*:
    - changes register count.
  - affects *cycle-time*:
    - changes path delays between register pairs.
- Solvable in polynomial time.

Assumptions

- Vertex delay is constant:
  - No *fanout delay dependency.*
- Graph topology is invariant:
  - No logic transformations.
- Synchronous implementation:
  - Cycles have *positive* weights.
  - Edges have *non-negative* weights.
- Consider *topological* paths:
  - No false path analysis.

Retiming

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- Retiming of a vertex:
  - Integer.
  - Registers moved from output to input.
- Retiming of a network:
  - Vector of vertex retiming.
- A family of equivalent networks are specified by:
  - The original network.
  - A retiming vector.

Example

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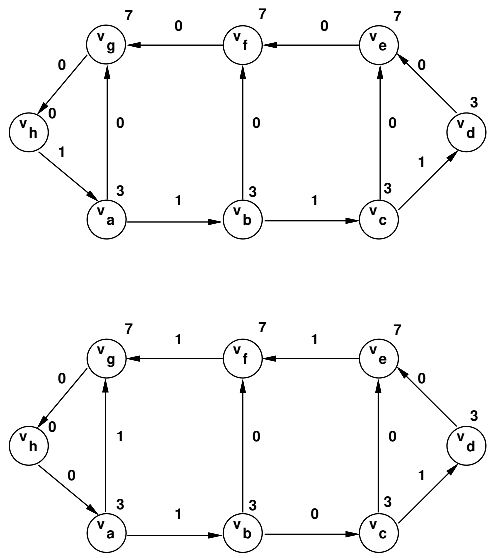

Definitions and properties

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- Definitions:
  - $w(v_i, v_j)$ – weight of edge (v_i, v_j).
  - $(v_i, \ldots, v_j)$ – path from v_i to v_j.
  - $d(v_i, \ldots, v_j)$– path delay from v_i to v_j.
- Properties:
  - Retiming of an edge (v_i, v_j):
    - $\tilde{w}_{ij} = w_{ij} + r_j - r_i$.
  - Retiming of a path $(v_i, \ldots, v_j)$:
    - $\tilde{w}(v_i, \ldots, v_j) = w(v_i, \ldots, v_j) + r_j - r_i$.
  - Cycle weights are invariant.

Example

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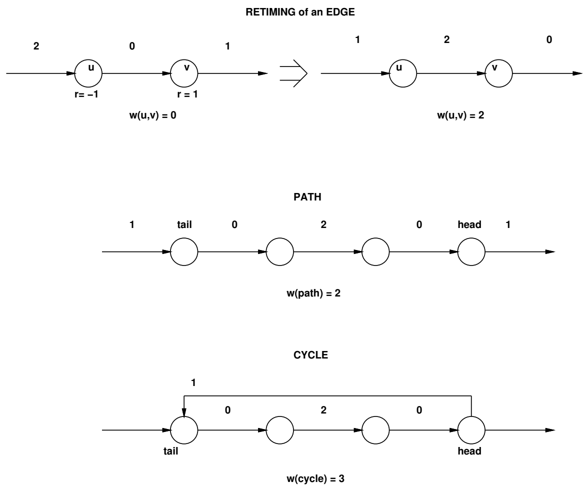

Legal retiming

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- Clock period ϕ.
- Retiming vector such that:
  - No edge weight is negative: $\tilde{w}_{ij} = w_{ij} + r_j - r_i \geq 0 \quad \forall i, j$.
  - Each path $(v_i, \ldots, v_j)$ with $d(v_i, \ldots, v_j) > \phi$ has at least one register: $\tilde{w}(v_i, \ldots, v_j) = w(v_i, \ldots, v_j) + r_j - r_i \geq 1 \; \forall i, j$.
- Fact:
  - Original graph has no cycles with weight ≤ 0 $\Rightarrow$ new graph has no cycles with weight ≤ 0.

Refined analysis

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- Least register path:
  - $W(v_i, v_j) = \min w(v_i, \ldots, v_j)$.
  - Over all paths between v_i and v_j.
- Critical delay:
  - $D(v_i, v_j) \;=\; \max d(v_i, \ldots, v_j)$
  - Over all the paths from v_i to v_j with weight $W(v_i, v_j)$.
- There exists a vertex pair v_i, v_j whose $D(v_i, v_j)$ bounds the cycle-time.

Example

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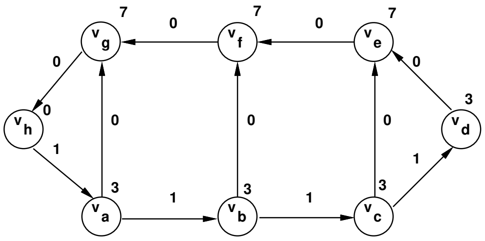

- Vertices: v_a, v_e.
- Paths: (v_a, v_b, v_c, v_e) and $(v_a, v_b, v_c, v_d, v_e)$.
- $W(v_a, v_e) = 2$ and $D(v_a, v_e) = 16$.

Minimum cycle-time retiming problem

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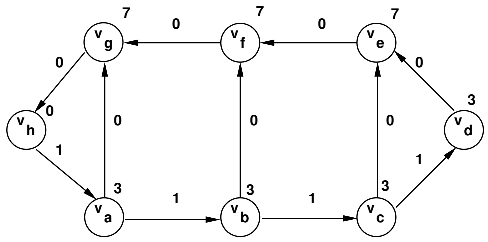
- Find minimum value of the clock period ϕ such that there exist a retiming vector where:
  - $r_i - r_j \leq w_{ij} \quad \forall (v_i, v_j) \in E$
  - $r_i - r_j \leq W(v_i, v_j) - 1 \quad \forall v_i, v_j | D(v_i, v_j) > \phi$.
- Solution:
  - Given a value of ϕ:
    - solve linear constraints.
    - methods:
      - Bellman-Ford or derivate.
      - MILP.
      - Relaxation.

Minimum cycle-time retiming algorithm

- Compute all-pair $W(v_i, v_j)$ and $D(v_i, v_j)$.
  - Warshall-Floyd algorithm ($O(V^3)$).
- Sort the elements of **D** in decreasing order.
- Binary search for a ϕ in $D(v_i, v_j)$ such that:
  - There exist a legal retiming.
  - Bellman-Ford algorithm ($O(V^3)$).
- Remarks:
  - Result is a global optimum.
  - Overall complexity is $O(V^3 logV)$.

Example

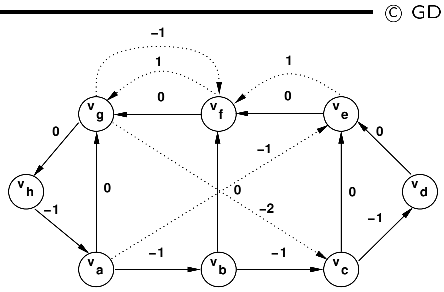


- Constraints (first type):
  - $r_a - r_b \leq 1$ or equivalently $r_b \geq r_a - 1$
  - $r_c - r_b \leq 1$ or equivalently $r_c \geq r_b - 1$
  - $\cdots$

Example

- Sort elements of **D**:
  - $(33, 30, 27, 26, 24, 23, 21, 20, 19,$ $17, 16, 14, 13, 12, 10, 9, 7, 6, 3)$.
- Select: $\phi = 19$:
  - PASS.
- Select: $\phi = 13$:
  - PASS.
- Select: $\phi < 13$:
  - FAIL.

Example
$\phi = 13$



- Constraints (second type):
  - $r_a - r_e \leq 2 - 1$ or equivalently $r_e \geq r_a - 1$
  - $r_e - r_f \leq 0 - 1$ or equivalently $r_f \geq r_e + 1$
  - $r_f - r_g \leq 0 - 1$ or equivalently $r_g \geq r_f + 1$
  - $r_g - r_f \leq 2 - 1$ or equivalently $r_f \geq r_g - 1$
  - $r_g - r_c \leq 3 - 1$ or equivalently $r_c \geq r_g - 2$

Example
$\phi = 13$

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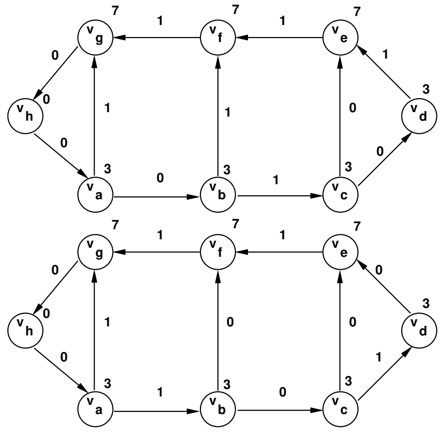

- Solutions:
  - $-[12232100]^T$ (LP from v_h).
  - $-[11222100]^T$ (Equivalent solution).

Relaxation-based algorithm
Rationale

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- Look for paths with excessive delay.
- Make them shorter by pulling closer the terminal register.
  - Some other paths may become too long.
  - Those paths whose tail has been moved.
- Use an iterative approach.

Relaxation-based algorithm

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- Define vertex *data ready* time:
  - Total delay from register boundary.
- Iterative approach:
  - Find vertices with *data ready* time $> \phi$.
  - Retime these vertices by 1.
- Properties:
  - Finds legal retiming in at most $|V|$ iterations, if one exists.

Example
$\phi = 13$

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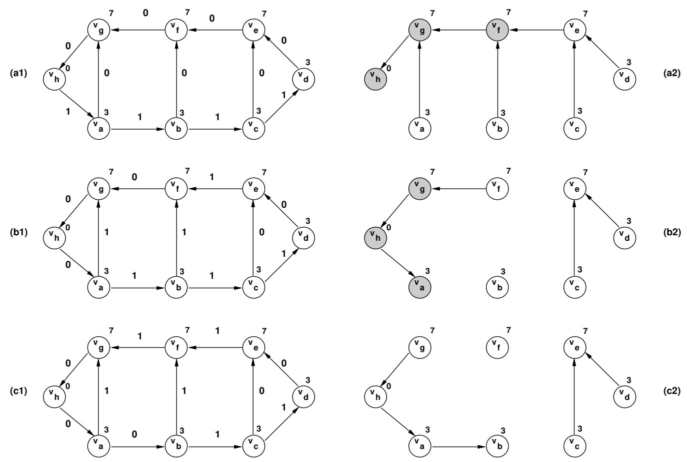


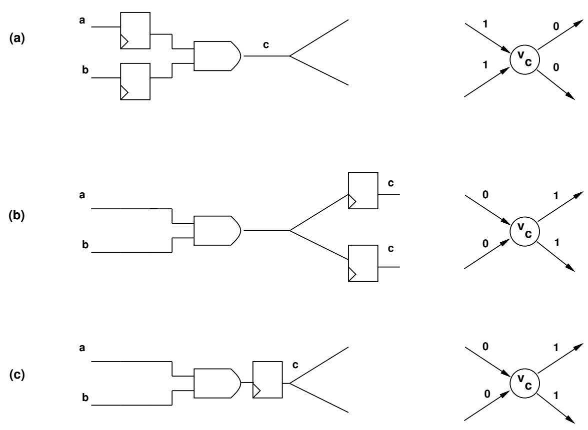
Example

- Data-ready times:
  - $t_a = 3; t_b = 3; t_c = 3; t_d = 3; t_e = 10;$ $t_f = 17; t_g = 24; t_h = 24.$
- Retime: $\{t_f, t_g, t_h\}$ by 1.
- Data-ready times:
  - $t_a = 17; t_b = 3; t_c = 3; t_d = 3; t_e = 10;$ $t_f = 7; t_g = 14; t_h = 14.$
- Retime:
  - $\{t_a, t_g, t_h\}$ by 1.
- Data-ready times:
  - $t_a = 10; t_b = 13; t_c = 3; t_d = 3; t_e = 10;$ $t_f = 7; t_g = 7; t_h = 7,$
  - TIMING FEASIBLE NETWORK !

Minimum area retiming problem

- Find a retiming vector that minimizes the number of registers.
- Simple area modeling:
  - Every pos.-weighted edge $\rightarrow$ register.
  - Total register area cost equals total of weights.
- Register sharing model:
  - Every set of positively-weighted edges with common tail $\rightarrow$ shift-register.
  - Register area cost equals maximum of weights on outgoing edges.

Example



Minimum area retiming simple model

- Register variation at vertex v:
  - $r_v \cdot (indegree(v) - outdegree(v)).$
- Total area variation:
  - $\sum r_v \cdot (indegree(v) - outdegree(v)).$
- Area minimization problem:
  - min
    - $\sum_{v \in V} r_v \cdot (indegree(v) - outdegree(v)).$
  - s.t.
    - $r_i - r_j \leq w(v_i, v_j)$ for every (v_i, v_j).

Minimum area retiming under cycle time constraint ϕ

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- min
  - $\sum_{v \in V} r_v \cdot (indegree(v) - outdegree(v))$.
- s.t.
  - $r_i - r_j \leq w(v_i, v_j)$ for every (v_i, v_j).
  - $r_i - r_j \leq W(v_i, v_j) - 1 \quad \forall v_i, v_j | D(v_i, v_j) > \phi$.

Minimum area retiming algorithm

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- Linear program.
- Transform into matching problem:
  - Edmonds-Karp algorithm.
  - Polynomial time.
- Remark:
  - Register sharing model
    can be transformed into the simple model.
  - Same solution algorithms.

Summary of retiming

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- Sequential optimization technique for:
  - Cycle time or register area.
- Applicable to:
  - Synchronous logic models.
  - Architectural data-path models:
    - Resources with delays.
- Exact algorithm in polynomial time.
- Problems:
  - Delay modeling.
  - Network granularity.