In Search of Semantic Models for Reconciling Futures and Transactional Memory

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TM and intra-transaction parallelism

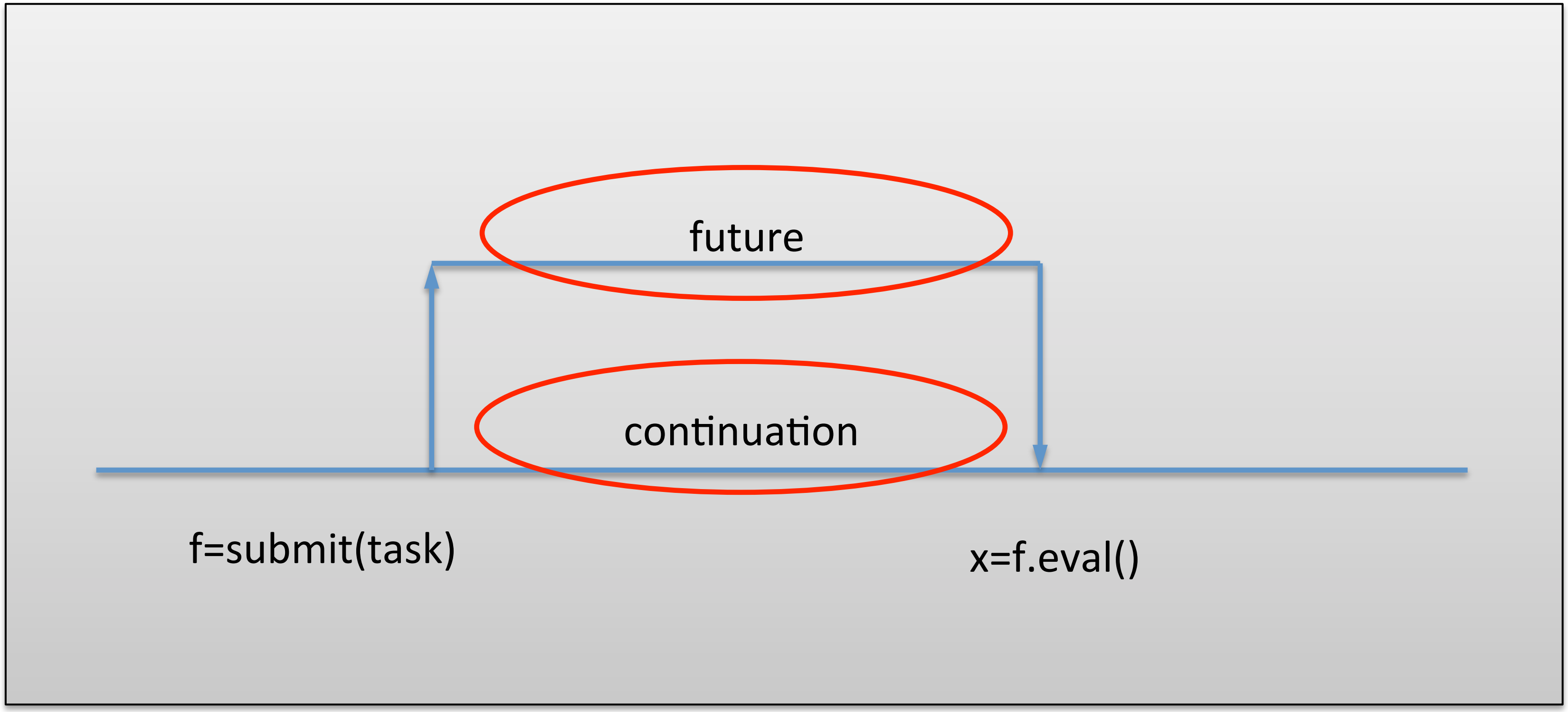
- TM has greatly matured over last decade:
  - hundreds of papers from academy and industry
  - hardware support in mainstream processors
  - integration in standard compilers
- Most literature assumes sequential execution of operations within transactions
- Can TM be used to exploit parallelism within transactions?

TM and parallel nesting

- Existing TMs that support intra-transaction parallelism offer *parallel nesting* abstraction:
  - fork-join semantics:
    - forking thread blocks till completion of nested txs
- To the best of our knowledge, no TM provides support for an alternative, more powerful abstraction:
  - the *future* abstraction

The Future abstraction

```
Future<T> f = submit(task); // submit an asynchronous task
 ...                        //do something else
T x = f.eval();             //pick up task's result
```

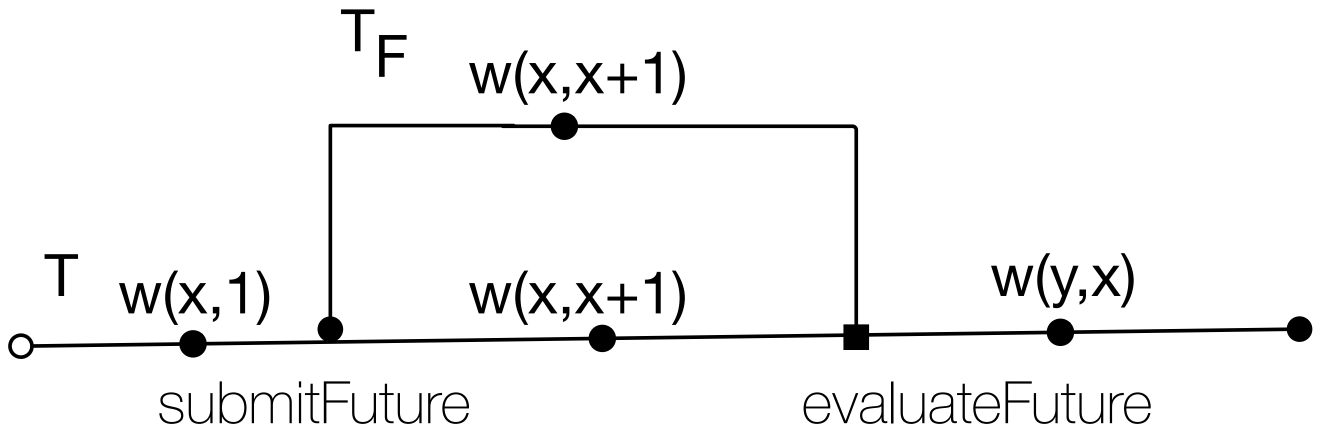


How to support Futures in TM?

- Basic idea – *Transactional Future*:
  - allow transactions to submit/evaluate futures
  - futures run as transactions that:
    - can access shared variables
    - can return some result value
  - a future and its continuation appear as atomic units

- 2 key issues:
  - which serialization orders should be allowed between futures and continuations?
  - how to define the boundaries of a continuation?

Transactional Futures Semantics: a basic example



- Intuitively we want to guarantee atomicity between T_F and its continuation…

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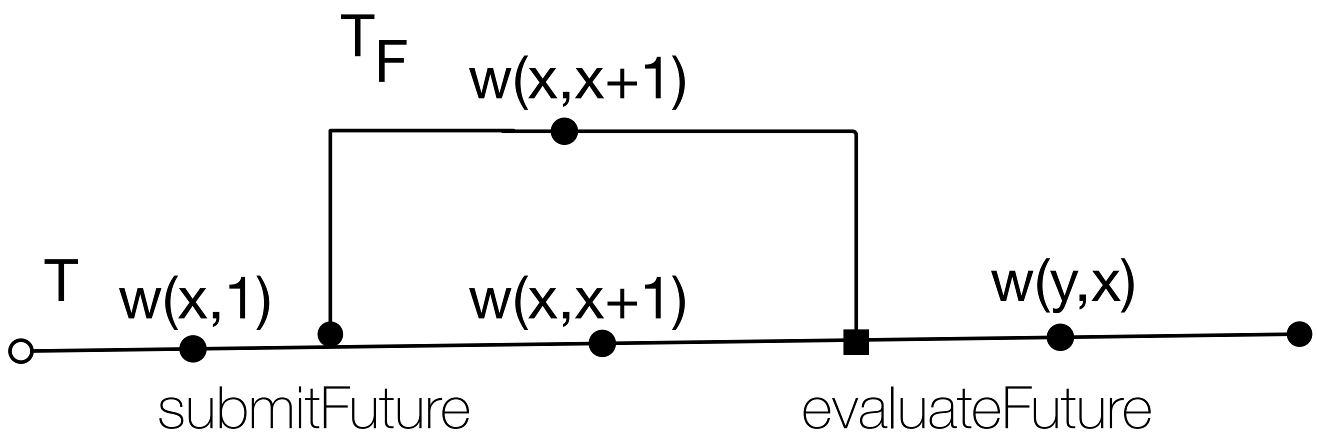

- …but what are the expected serialization orders between T_F and its continuation?

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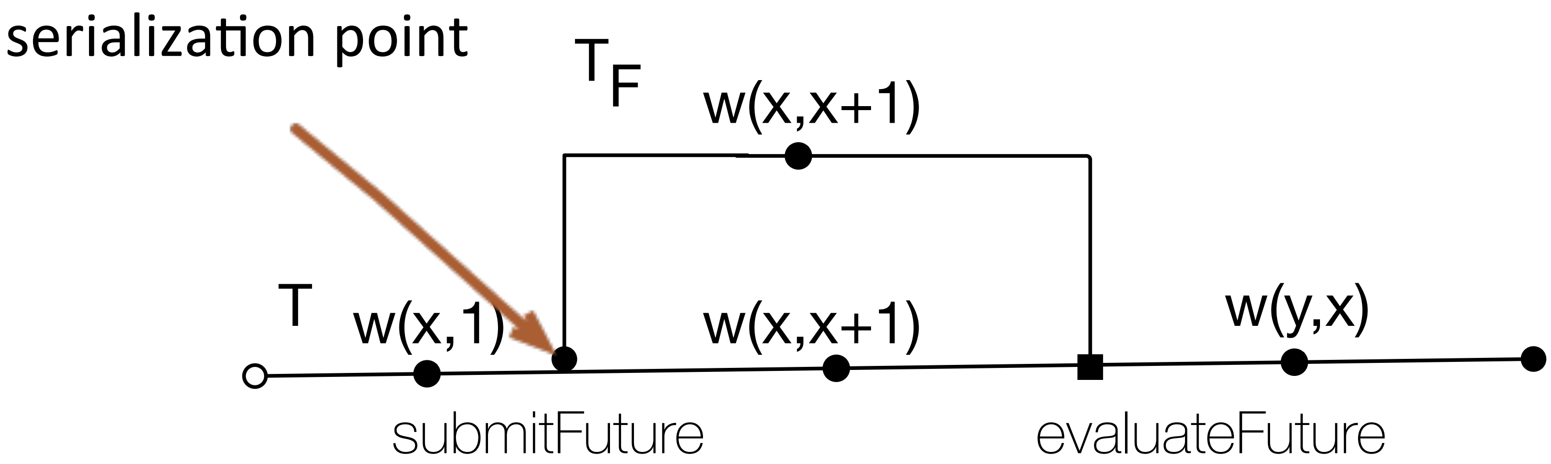
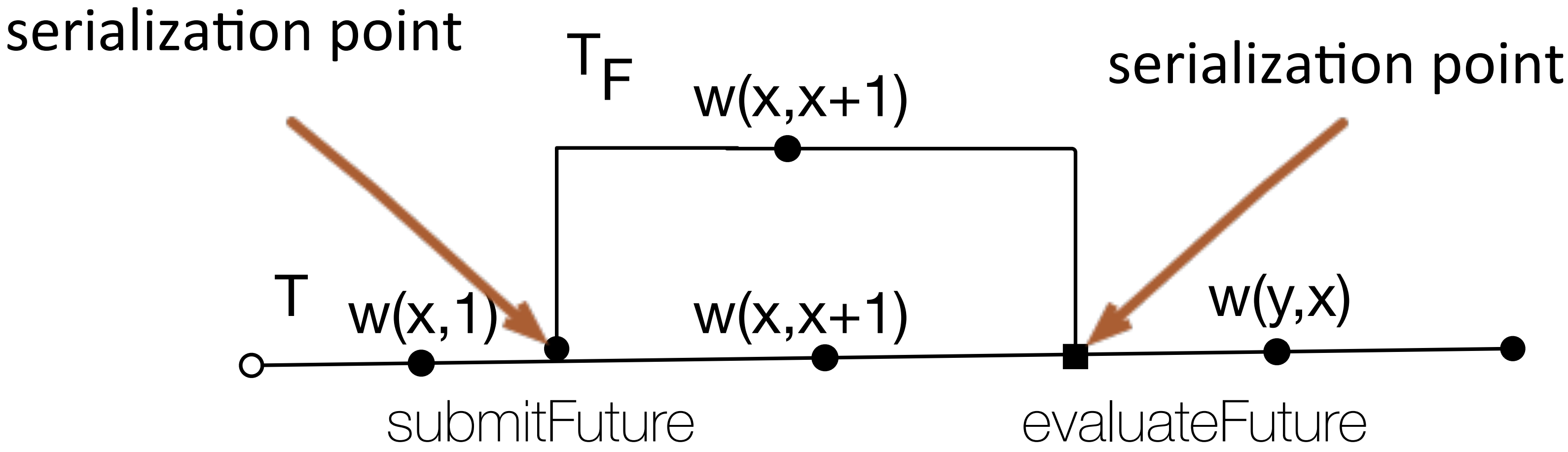


- …but what are the expected serialization orders between T_F and its continuation?
  - before T_F's continuation: strongly ordered

Transactional Futures Semantics: a basic example



- …but what are the expected serialization orders between T_F and its continuation?
  - before T_F's continuation: strongly ordered
  - either before or after T_F's continuation: weakly ordered

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- 2 key issues:
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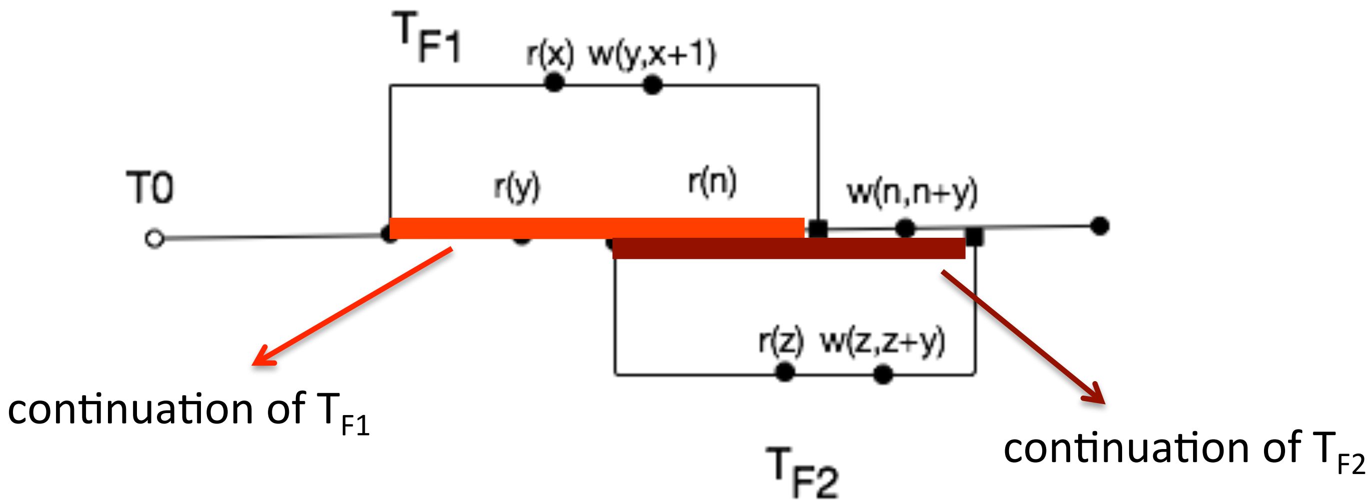
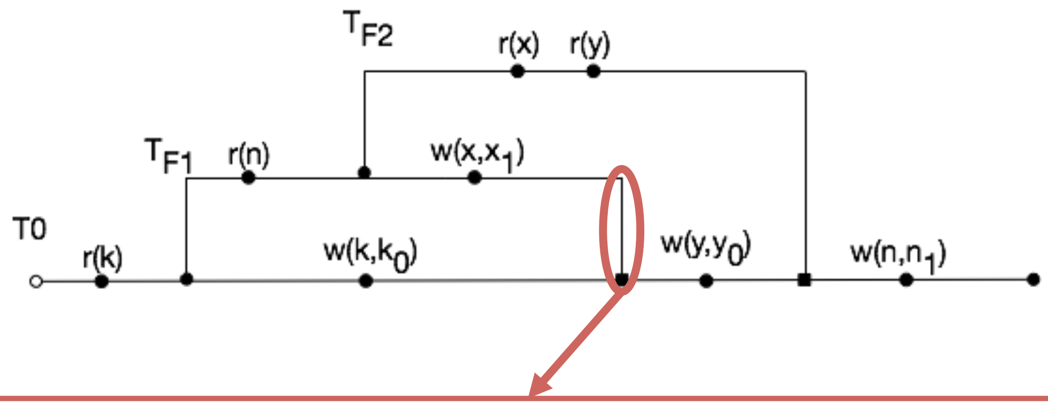
How to define continuations?

- The Future abstraction enables parallel computations with complex dependency graphs, e.g.:
  - submitting futures from within continuations
  - escaping transactional futures
    - within the same top-level transaction, or
    - submitted and evaluated in different top-level transact.
- **Pro**: great flexibility for expert programmers
- **Con:** non-trivial to define continuations

Submission of a future by a continuation



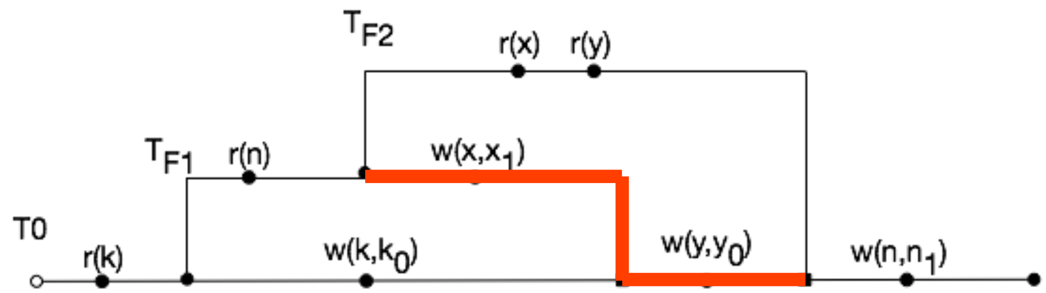
Escaping transactional future



Here T_{F1} returns the reference of T_{F2} to T0,
in order to allow T0 to evaluate T_{F2}

Escaping transactional future

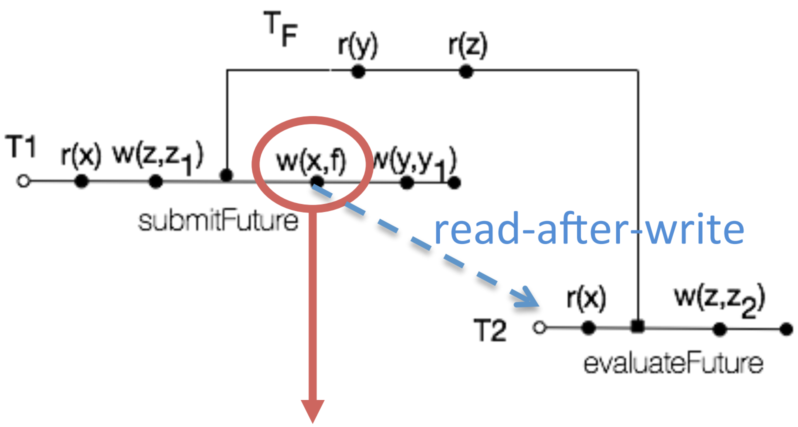
<u>Logic underlying definition of T_{F2} continuation:</u>
Sequence of causally-related operations that leads from T_{F2}'s submission to its evaluation



- Continuation of T_{F2} spans two transactional futures!
- T_{F2} should observe both writes on x and y or none!

Transactional future escaping from its top-level transaction

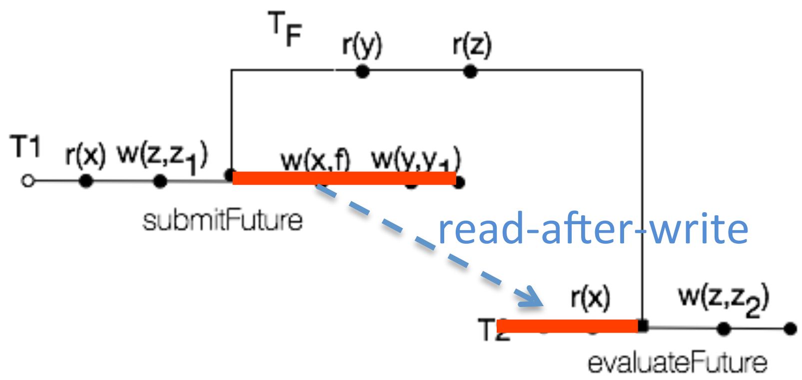
T_F is used as a communication means between T1 and T2.



T1 writes T_F's reference in variable x and commits.
This allows a different top-level transaction, e.g. T2, to evaluate T_F.

Transactional future escaping from its top-level transaction

<u>Logic underlying definition of T_F continuation:</u>
Sequence of causally-related operations that leads from T_F's submission to its evaluation



- Using the above rationale, a continuation can span two or more top-level transactions ➔ <u>*strongly atomic continuation*</u>
- Constrain T_F's continuation within the top-level tx that submitted T_F ➔ <u>*weakly atomic continuation*</u>

How to formalize these concepts?

- Via the Future Serialization Graph:
  - similar in spirit to transaction serialization graph
  - but aimed to:

1. allow for rigorous definition of futures and their continuations
2. capture ordering relations between futures and continuations

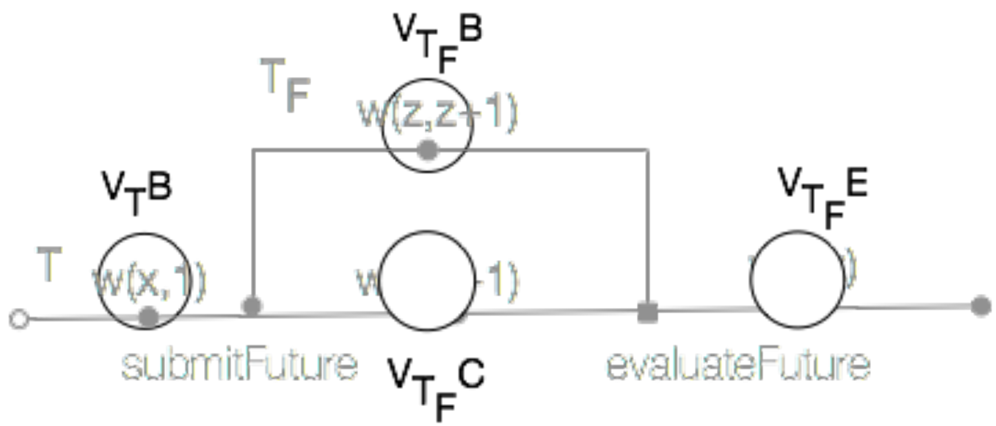
Future Serialization Graph

Vertexes:

V_T^B : all ops since tx begin to first {commit, abort, submit, eval}

V_T^C: all ops since subm. of a future to first {commit, abort, submit, eval}

V_T^E: all ops since evaluation of a future to first {commit, abort, submit, eval}

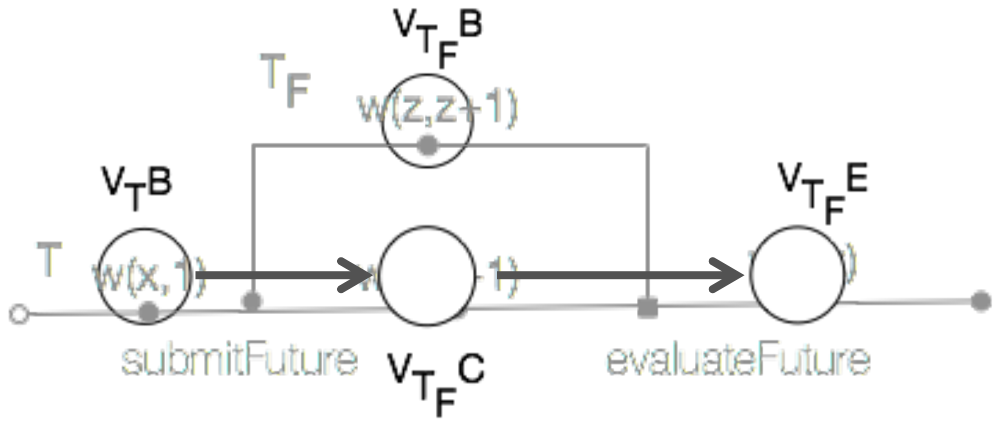


Future Serialization Graph

Edges:

V1→V2 , for each vertex V1, V2 in FSG s.t. :

- V1 and V2 are executed by the same thread *t* and *t* executes V1 before V2

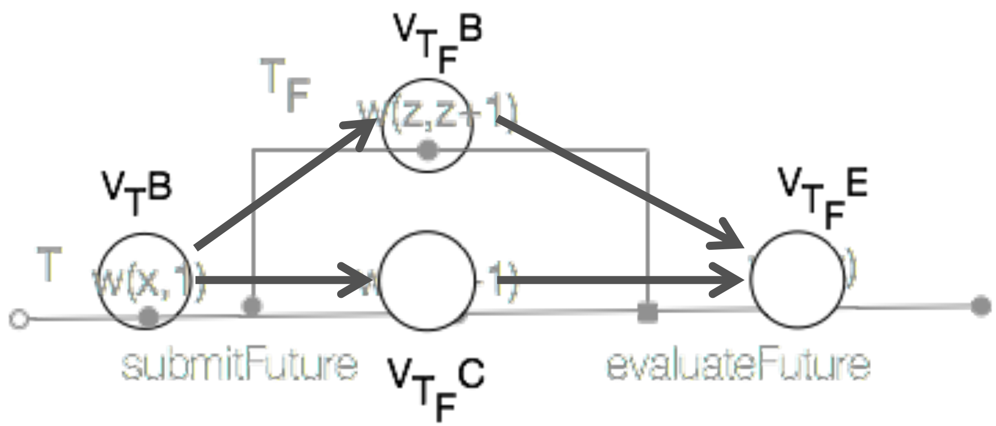


Future Serialization Graph

Edges:

For each transactional future T :

- $V_T^S \rightarrow V_T^B$: submission of a future precedes its execution
  (where V_T^S is the vertex in FSG containing T's submission)
- $V_T^B \rightarrow V_T^E$: evaluation of a future follows its execution

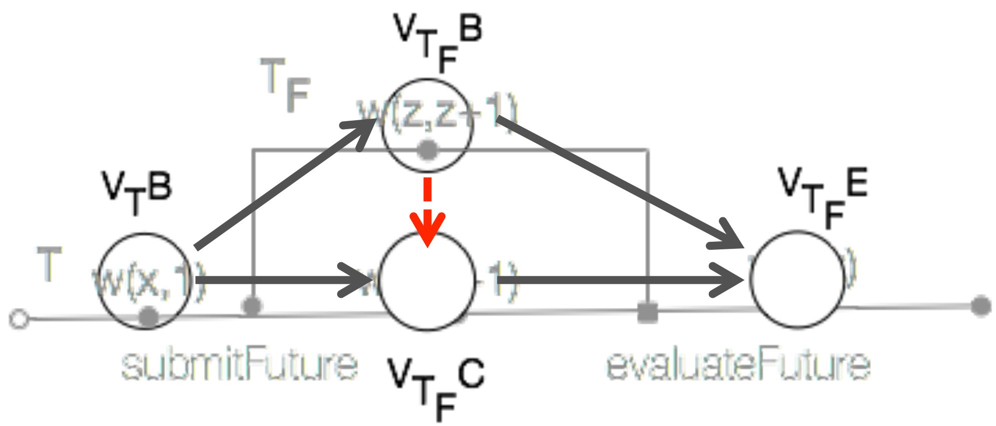


Future Serialization Graph

Edges:

For each strongly ordered transactional future T :

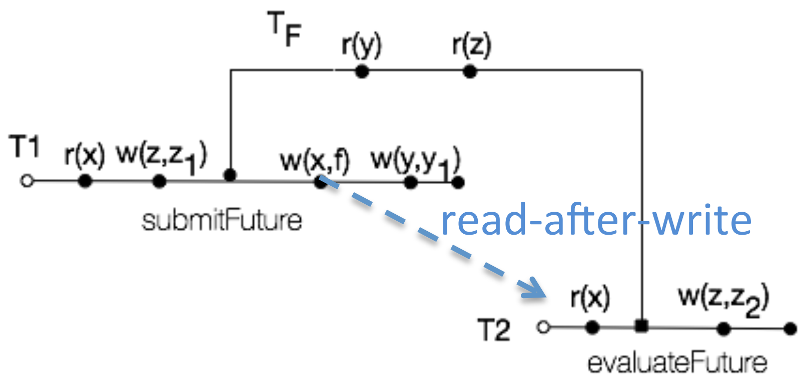
- $V_T^B \rightarrow V_T^C$: future precedes its continuation

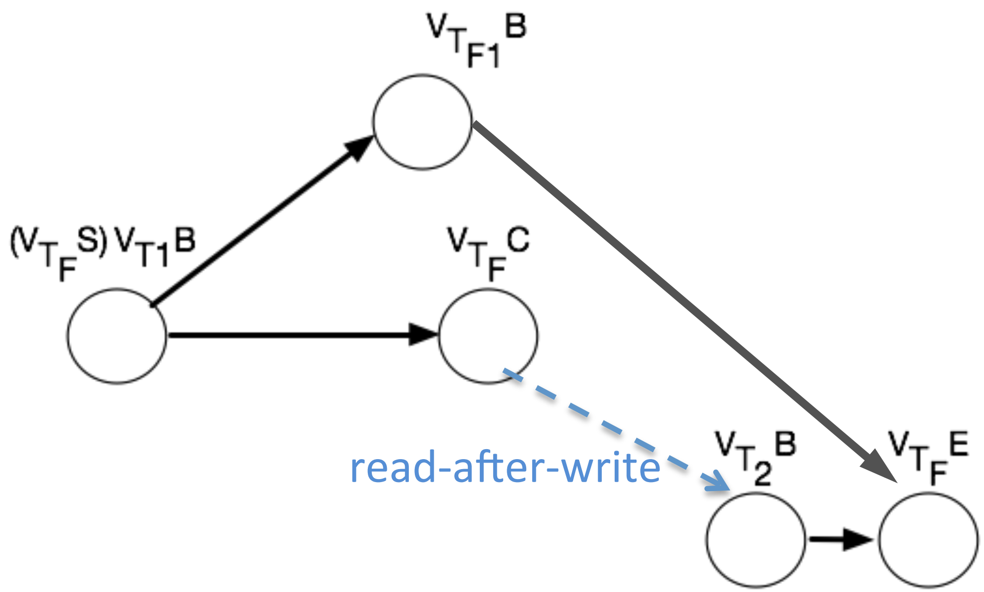


FSG+

Extension of FSG to include read-after-write dependencies:

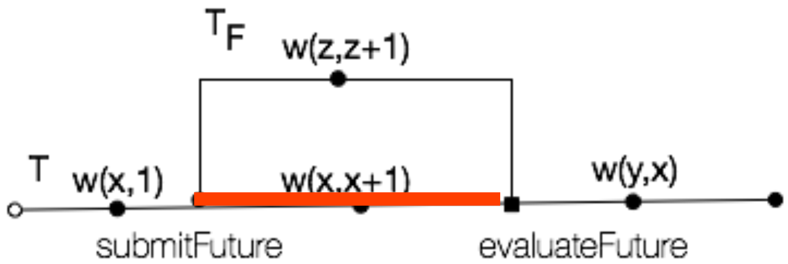
- captures causal relations among transactions that communicate futures' references via shared variables

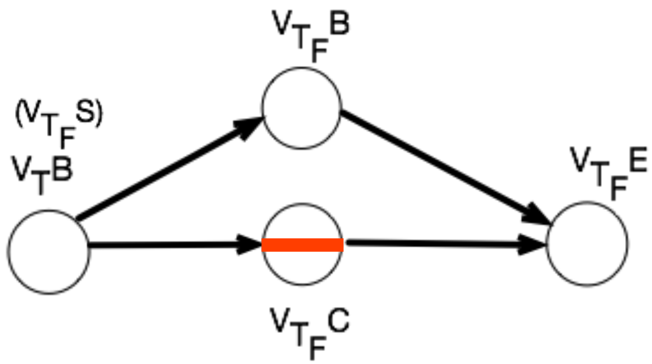


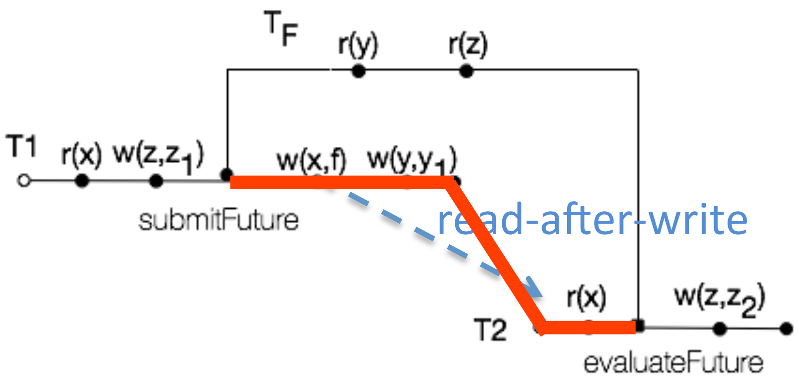


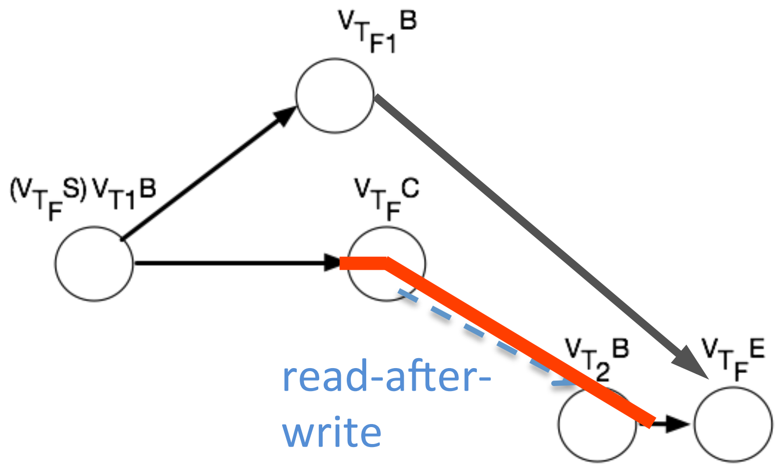
Strongly Atomic Continuations

- Strongly atomic continuation of a tx future T_F:
  - set of vertexes that connect $V_{T_F}{}^{C}$ to $V_{T_F}{}^{E}$ in FSG+



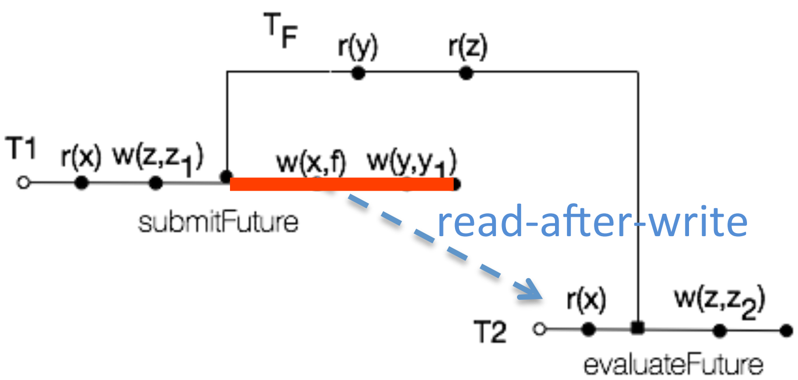


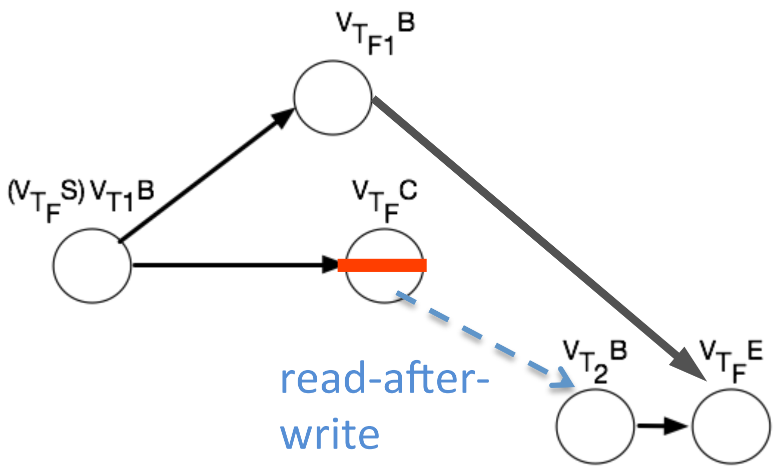




Weakly Atomic Continuations

- Weakly atomic continuation of a tx future T_F:
  - set of vertexes in FSG+ that connect $V_{T_F}{}^C$ to $V_{T_F}{}^E$
  - constraint to the top-level tx that submitted T_F





Using the FSG+

- The FSG+ defines the transactional futures semantics by restricting the admissible serialization orders of transactions
- …but can also be used by a graph-based concurrency control algorithm to ensure the desired semantics

Using the FSG+

- Intuition:
  - Enforce aciclicity of the FSG+ extended with the conflicts developed among transaction
- One important subtlety:
  - FSG+ can associate multiple vertexes to transactions and to futures/continuations:
    - if a conflict is developed from/to futures/transactions/ continuations that <u>include</u> multiple vertexes in the FSG+

    ➔ add edges from/to all of the vertexes that they <u>include</u>

Summary

- Futures represent a powerful abstraction to:
  - exploit intra-transaction parallelism
  - enable new synchronization and communication patterns for transactional programming
- First attempt to define semantics of futures in a transactional context:
  - graph-based specification of alternative properties for:
    - serialization orders between futures and continuations
    - definition of continuations

Open research questions

- Is the current formalization complete?
- Can alternative formalisms be used?
- Which are the theoretical costs/complexity of the various semantics?
- Can these semantics be implemented efficiently in a practical system?

Thank you.
Questions?

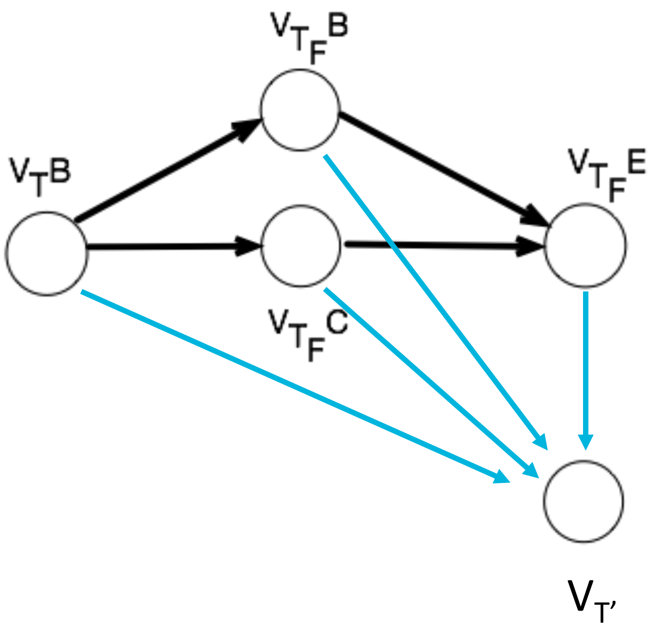
Backup Slides

Inclusion of an operation in a transaction

- An operation *op* is ***included*** in a transaction T if there is a path in the FSG:
  - from the vertex associated with the begin of T
  - to the vertex associated with the commit/abort of T
  - that passes via the vertex associated with *op*
- A transaction T includes:
  - all and only the operations issued by T,
  - by any non-escaping future submitted by T,
  - and, recursively, by T 's futures

Atomicity between top level transactions

- Let *op* be an operation included in a top-level transaction T
- Assume *op* develops a data dependency to/from an operation *op*' included in a different top-level transaction T'
- Add a data dependency edge from all the vertexes included in T to/from all the vertexes included in T'



Atomicity between futures and continuations

- Let *op* be an operation included in a transactional future T
- Assume *op* develops a data dependency to/from an operation *op'* included in the continuation of T
- Add a data dependency edge from all the vertexes included in T to/from all the vertexes included in the continuation of T