OFFICE OF FINANCIAL RESEARCH

Contract as Automaton

The Computational Representation of Financial Agreements

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Disclaimers and Credits

Views and opinions expressed are those of the speaker(s) and do not necessarily represent official OFR positions or policy.

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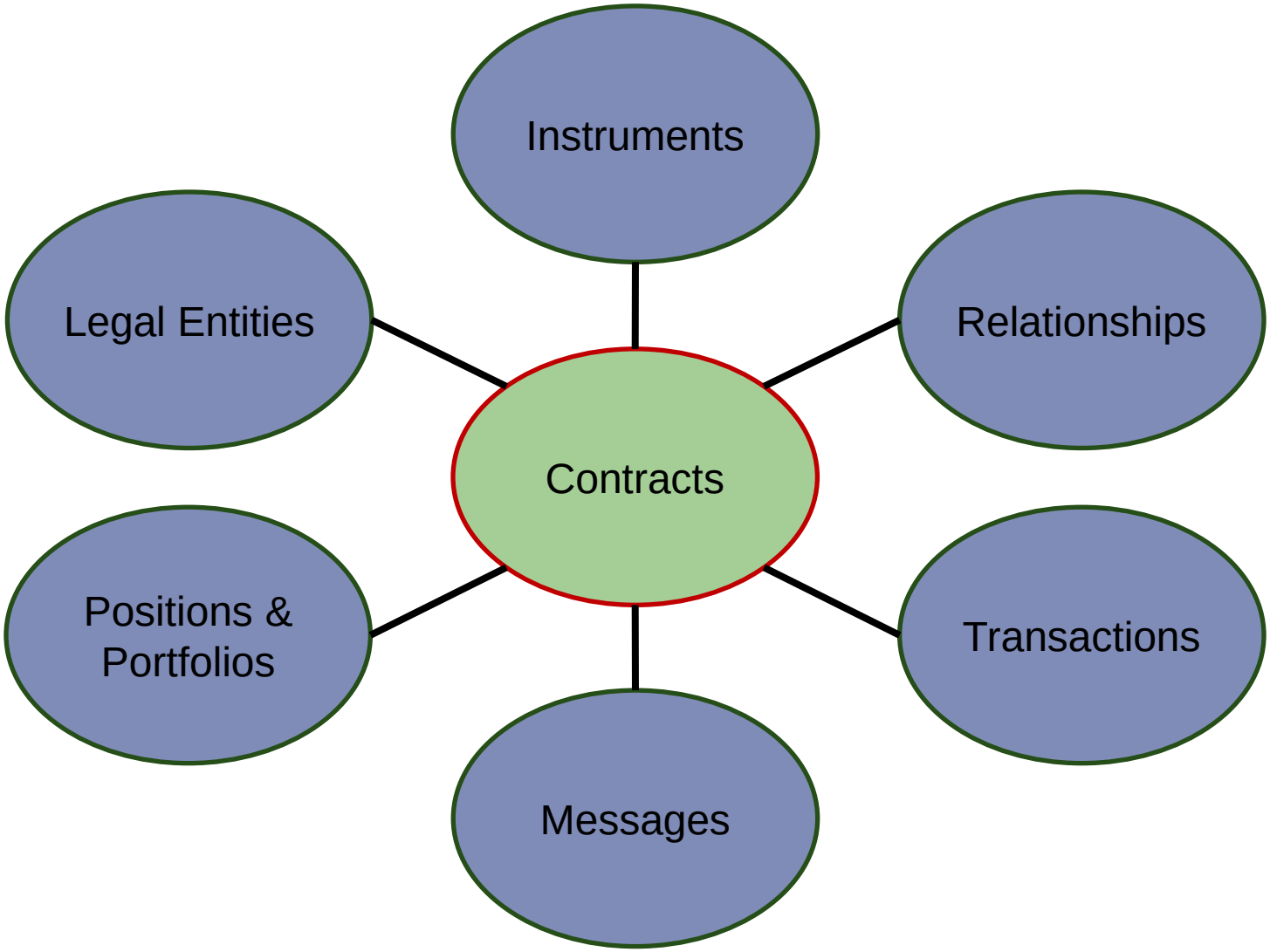
Measuring Financial Contracts



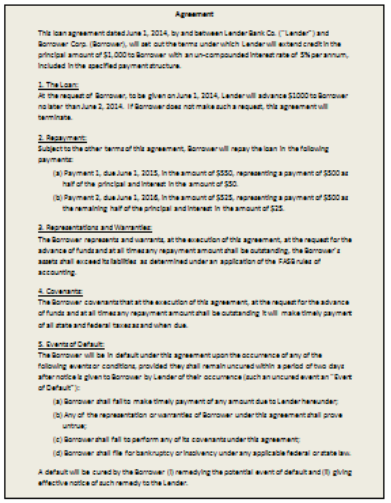
Computational Contracts

- **Key insights**
  - Financial contracts are central to understanding the financial ***system***
  - Financial agreements aid coordination by alleviating "social uncertainty"
  - Formal modeling of structure makes it accessible to programmatic analysis
  - ***Financial contracts are structured internally as state-transition systems***
- **Proof of concept**
  - A single, simple loan agreement, stated in traditional legalese
  - Underlying structure of that agreement as a discrete finite automaton (DFA)
  - Three (interchangeable) representations of the structure:
    - Graphical
    - Tabular
    - Regular expression
  - Discretization and finiteness are crucial to managing complexity

A "Toy" Loan Agreement

Simple two-page loan contract

1. The Loan: $1000, June 1, 2014
2. Repayment:
   - Payment 1, due June 1, 2015: $550
   - Payment 2, due June 1, 2016: $525
3. Representations and Warranties
4. Covenants
5. Events of Default:
   - Borrower fails to make timely payment
   - Reps or warranties prove untrue
   - Borrower fails any covenants
   - Borrower files for bankruptcy
6. Acceleration on Default
7. Choice of Law
8. Amendments and Waivers
9. Courts and Litigation
10. Time of the Essence; No Pre-Payment
11. Notices



Agreement

This loan agreement dated June 1, 2014, by and between Lender Bank Co. ("Lender") and Borrower Corp. (Borrower), will set out the terms under which Lender will extend credit in the principal amount of $1,000 to Borrower with an un-compounded interest rate of 3% per annum, included in the specified payment structure.

1. The Loan:
At the request of Borrower, to be given on June 1, 2014, Lender will advance $1000 to Borrower no later than June 2, 2014. If Borrower does not make such a request, this agreement will terminate.

2. Repayment:
Subject to the other terms of this agreement, Borrower will repay the loan in the following payments:

(a) Payment 1, due June 1, 2015, in the amount of $550, representing a payment of $500 as half of the principal and interest in the amount of $50.

(b) Payment 2, due June 1, 2016, in the amount of $525, representing a payment of $500 as the remaining half of the principal and interest in the amount of $25.

3. Representations and Warranties:
The Borrower represents and warrants, at the execution of this agreement, at the request for the advance of funds and at all times any repayment amount shall be outstanding, the Borrower's assets shall exceed its liabilities as determined under an application of the FASB rules of accounting.

4. Covenants:
The Borrower covenants that at the execution of this agreement, at the request for the advance of funds and at all times any repayment amount shall be outstanding it will make timely payment of all state and federal taxes as and when due.

5. Events of Default:
The Borrower will be in default under this agreement upon the occurrence of any of the following events or conditions, provided they shall remain uncured within a period of two days after notice is given to Borrower by Lender of their occurrence (such an uncured event an "Event of Default"):

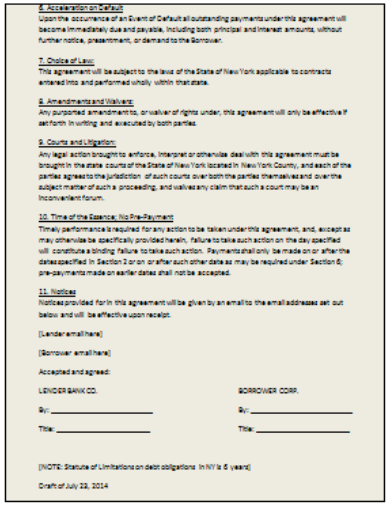
(a) Borrower shall fail to make timely payment of any amount due to Lender hereunder;

(b) Any of the representation or warranties of Borrower under this agreement shall prove untrue;

(c) Borrower shall fail to perform any of its covenants under this agreement;

(d) Borrower shall file for bankruptcy or insolvency under any applicable federal or state law.

A default will be cured by the Borrower (i) remedying the potential event of default and (ii) giving effective notice of such remedy to the Lender.



6. Acceleration on Default:
Upon the occurrence of an Event of Default all outstanding payments under this agreement will become immediately due and payable, including both principal and interest amounts, without further notice, presentment, or demand to the Borrower.

7. Choice of Law:
This agreement will be subject to the laws of the State of New York applicable to contracts entered into and performed wholly within that state.

8. Amendments and Waivers:
Any purported amendment to, or waiver of rights under, this agreement will only be effective if set forth in writing and executed by both parties.

9. Courts and Litigation:
Any legal action brought to enforce, interpret or otherwise deal with this agreement must be brought in the state courts of the State of New York located in New York County, and each of the parties agrees to the jurisdiction of such courts over both the parties themselves and over the subject matter of such a proceeding, and waives any claim that such a court may be an inconvenient forum.

10. Time of the Essence; No Pre-Payment:
Timely performance is required for any action to be taken under this agreement, and, except as may otherwise be specifically provided herein, failure to take such action on the day specified will constitute a binding failure to take such action. Payments shall only be made on or after the dates specified in Section 2 or on or after such other date as may be required under Section 6; pre-payments made on earlier dates shall not be accepted.

11. Notices:
Notices provided for in this agreement will be given by an email to the email addresses set out below and will be effective upon receipt.

[Lender email here]

[Borrower email here]

Accepted and agreed:

LENDER BANK CO. BORROWER CORP.

By: _____ By: _____

Title: _____ Title: _____

[NOTE: Statute of Limitations on debt obligations in NY is 6 years]

Draft of July 23, 2014

Deterministic Finite Automaton (DFA)

- **A deterministic finite automaton (DFA) is defined by a 5-tuple:**
  - Finite set of states ($\boldsymbol{Q}$)
  - Finite set of input symbols (information/events) called the alphabet ($\boldsymbol{\Sigma}$)
  - Transition function ($\boldsymbol{\delta} : \boldsymbol{Q} \times \boldsymbol{\Sigma} \rightarrow \boldsymbol{Q}$)
  - Start state ($\boldsymbol{q}_0 \in \boldsymbol{Q}$)
  - Set of accept (end) states ($\boldsymbol{F} \subseteq \boldsymbol{Q}$)

- **Three representations (at least):**
  - Graphical (depiction of states and transitions among them)
  - Lists (of $\boldsymbol{Q}$, $\boldsymbol{\Sigma}$ and $\boldsymbol{\delta}$)
  - Regular expression (shorthand grammar of acceptable event sequences)

Representation I: Graphical

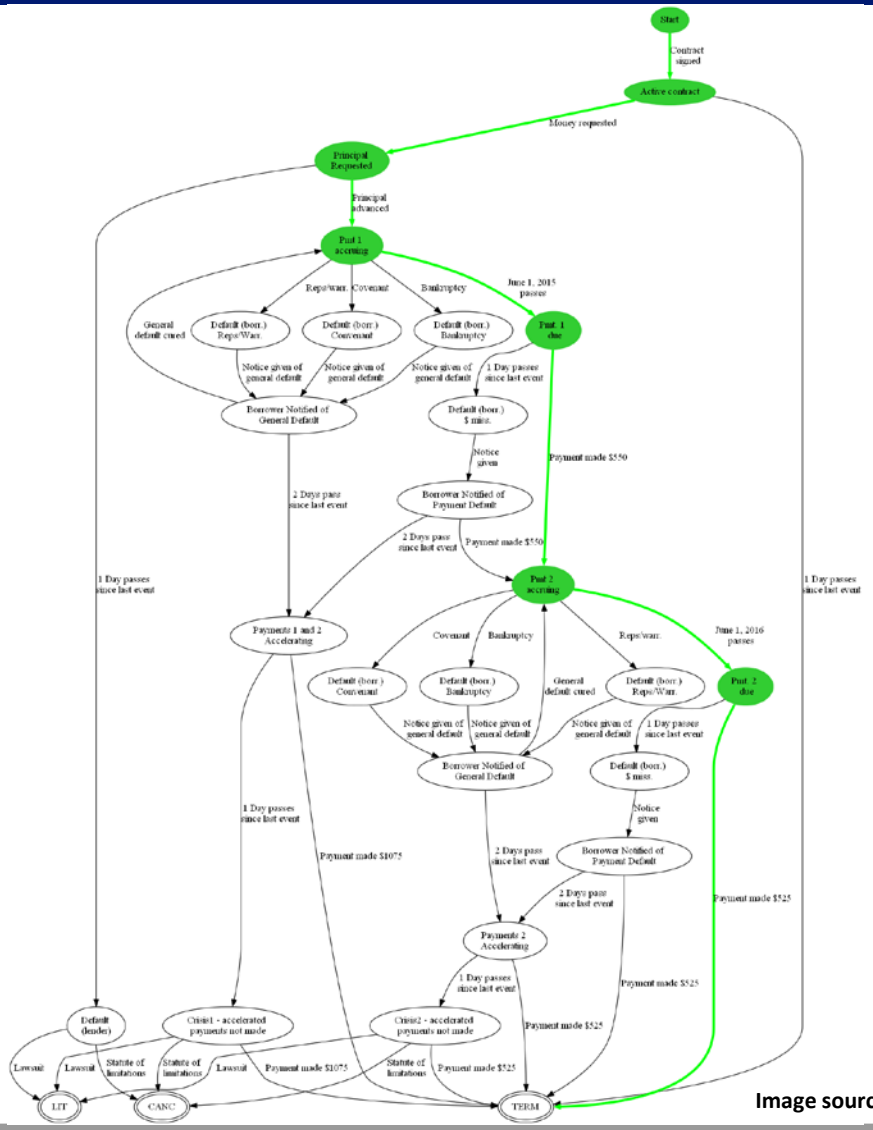


Image source: OFR analysis

DFA as a chain of event and consequence:

- Start state ($\boldsymbol{q}_0$) at the top
- Terminal states (3) at bottom
- "Happy" or intended path traced in green
- More "interesting" ramifications traced in black

Representation I: Graphical close-up

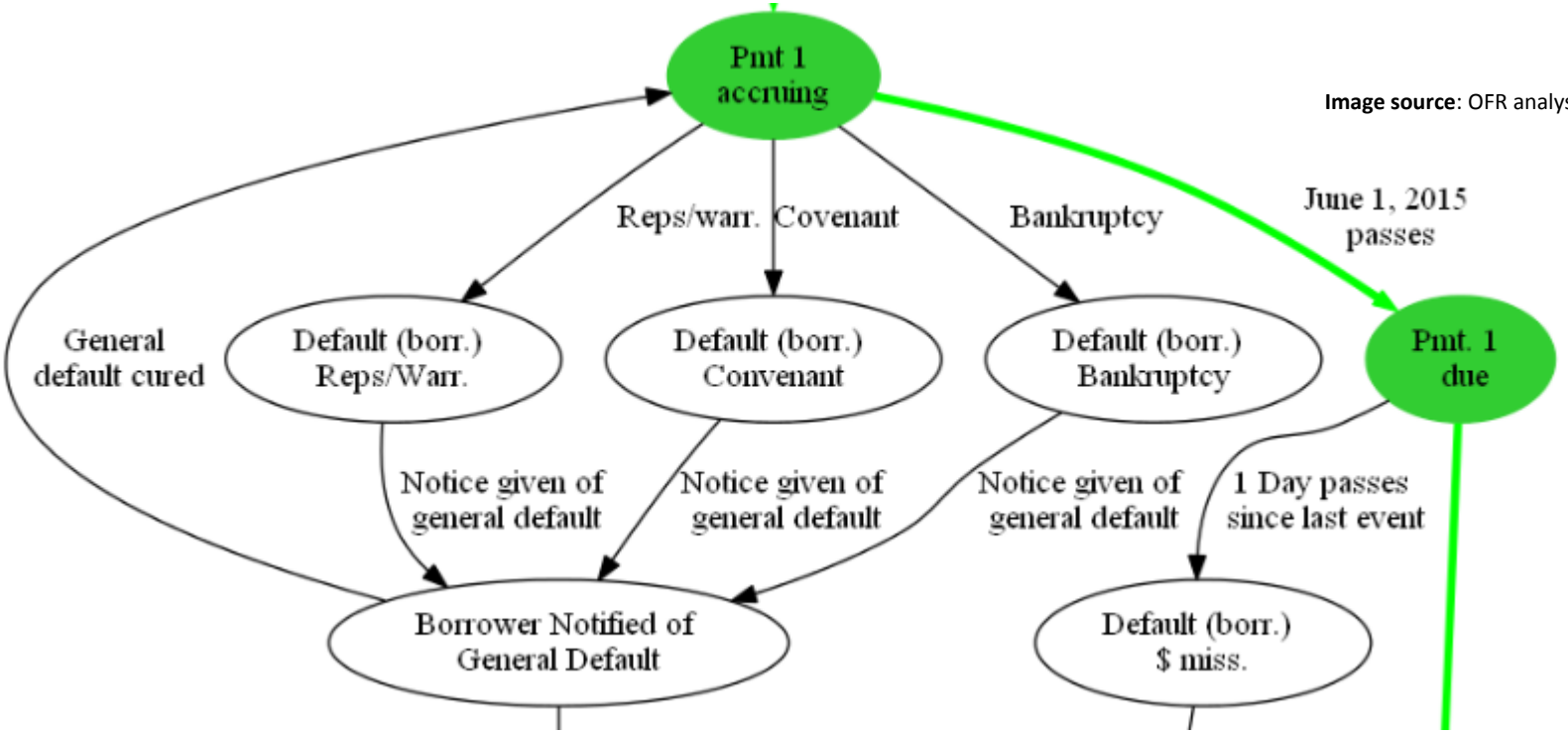


Image source: OFR analysis

From the state [*Pmt 1 accruing*], four transitions are possible:

- Three types of default:
  - Reps/warranties
  - Covenant
  - Bankruptcy
- Due date for first payment arrives <*June 1, 2015 passes*>

Representation II: Tabular

State	Label	Natural Language Consequences and Correlates (Λ)	Sec
start ◊	Start	Contract is fully specified; key information (payment dates, notice addresses and procedures, choice of law and dispute process) delivered	7, 9, 11
q0 ◊	Active contract	Contract is fully signed/executed	
q1 ◊	Principal Requested	Borrower's has requested and awaits $1,000	1
P1 ◊	Pmt 1 accruing		
P1d ◊	Pmt. 1 due		
P2 ◊	Pmt 2 accruing		
P2d ◊	Pmt. 2 due		
Dl	Default (lender)	Lender has failed to deliver principal	5
Acc1	Payments 1 and 2 Accelerating	Accelerated payment due is $1075	6
Acc2	Payments 2 Accelerating	Accelerated payment due is $525	6
Db0_1	Default (borr.) payment missed	Borrower has failed to make first payment in a timely fashion, and should be notified	5
Dbcv_1	Default (borr.) Covenant	Borrower violates covenant(s), and should be notified	5
Dbrw_1	Default (borr.) Reps/Warr.	Borrower breaches reps. and/or warranties; should be notified	5
Dbbkr_1	Default (borr.) Bankruptcy	Borrower files for bankruptcy or insolvency; should be notified	5
Nb0_1 Δ	Borr. notified of payment default	Borrower has 2 days to pay, or all payments accelerate	5
Nbnpd_1 Δ	Borr. notified of general default	Borrower has 2 days to pay, or all payments accelerate	5
Db0_2	Default (borr.) payment missed	Borrower has failed to make first payment in a timely fashion, and should be notified	5
Dbcv_2	Default (borr.) Convenant	Borrower violates covenant(s), and should be notified	5
Dbrw_2	Default (borr.) Reps/Warr.	Borrower breaches reps. and/or warranties; should be notified	5
Dbbkr_2	Default (borr.) Bankruptcy	Borrower files for bankruptcy or insolvency; should be notified	5
Nb0_2 Δ	Borr. notified of payment default	Borrower has 2 days to pay, or all payments accelerate	5
Nbnpd_2 Δ	Borr. notified of general default	Borrower has 2 days to pay, or all payments accelerate	5
xT *	TERM	Contract is fulfilled in accordance with its terms	
xL *	LIT	A legal action is brought to enforce, interpret or otherwise deal with the agreement in the state courts of the State of New York located in New York County and that the results of this action will replace the computation of the contract	9
xC *	CANC	Contract is canceled due to the passing of time beyond the statute of limitations or canceled because of modification or termination by mutual agreement of the parties	8
Crisis1	Crisis1 – accel. payments not made	Payments accelerated, but borrower has not responded	6
Crisis2	Crisis2 – accel. payments not made	Payments accelerated, but borrower has not responded	6

◊ *States on the "happy" path of the contract lifecycle*
Δ *Default states*
* *Terminal states*

ID	Label	Natural Language Event Specification	Section
A	Contract signed	Contract is signed to bind all parties	
B	1 Day passes since last event	June 1, 2014 passes	1
C	Money requested	Borrower gives request for loan of $1,000	1
D	Lawsuit	A legal action is brought to enforce, interpret or otherwise deal with the agreement in the state courts of the State of New York located in New York County.	
E	Statute of limitations	June 1, 2020 passes – the Statute of Limitations on debt obligations in New York is six years	
F	Principal advanced	Lender advances $1,000 no later than June 2, 2014	1
G	June 1, 2015 passes	Payment 1 due on June 1, 2015	2(a)
H	Reps/warr.	The Borrower's assets exceed its liabilities as determined under an application of the FASB rules of accounting	3, 5(b)
I	Covenant	The Borrower fails to make a timely payment of an amount of state or federal tax	4, 5(c)
J	Bankruptcy	The Borrower files for bankruptcy or insolvency under any applicable federal or state law	
K	Notice given	Notice given to Borrower of a failure to make timely payment of an amount due to Lender under this agreement	5
L	Notice given of general default	Notice given to Borrower of an event of default other than a failure to make timely payment of an amount due	5
M	Payment default cured	A payment-related event of default is cured	5
N	General default cured	A non-payment related event of default is cured	5
O	2 Days pass since last event	Two days elapse since last event/notice	5
P	June 1, 2016 passes	Payment 2 is due on June 1, 2016	2(b)
Q	Payment made $550		
R	Payment made $525		
S	Payment made $1075		
T	Cancel or modify	Contract in this form is canceled because of modification or termination by mutual agreement of the parties	8

Initial State	Event	Resulting State
start ◊	A	q0
q0	B	xT
q0 ◊	C	q1
q1	B	Dl
Dl	D	xL
Dl	E	xC
q1 ◊	F	P1
P1 ◊	G	P1d
P1d	B	Db0_1
P1	H	Dbrw_1
P1	I	Dbcv_1
P1	J	Dbbkr_1
Db0_1	K	Nb0_1
Dbcv_1	L	Nbnpd_1
Dbbkr_1	L	Nbnpd_1
Dbrw_1	L	Nbnpd_1
Nb0_1	Q	P2
Nbnpd_1	N	P1
Nb0_1	O	Acc1
Nbnpd_1	O	Acc1
Acc1	B	Crisis1
Acc1	S	xT
Crisis1	E	xC
Crisis1	D	xL
Crisis1	S	xT
P1d ◊	Q	P2

Initial State	Event	Resulting State
P2 ◊	P	P2d
P2d	B	Db0_2
P2	H	Dbrw_2
P2	I	Dbcv_2
P2	J	Dbbkr_2
P2d ◊	R	xT
Db0_2	K	Nb0_2
Dbcv_2	L	Nbnpd_2
Dbbkr_2	L	Nbnpd_2
Dbrw_2	L	Nbnpd_2
Nb0_2	R	xT
Nbnpd_2	N	P2
Nb0_2	O	Acc2
Nbnpd_2	O	Acc2
Acc2	B	Crisis2
Acc2	R	xT
Crisis2	E	xC
Crisis2	D	xL
Crisis2	R	xT

◊ *Transitions along the "happy" path of the contract lifecycle*
As noted above, only the transitions that result in a change of states are noted here; all un-noted transitions result in the state being unchanged.

State Space (27)

Q

Event Alphabet (20)

Σ

Transitions (45)

δ

Representation III: Regular Expression

`A(B|CB[ED])|`	*Rapid demise*
`ACF(G(BK)?)QPR |`	*Happy path*
`ACF([HIJ]LN)*(GBK|[HIJ]L)O(S|B[DES]) |`	*Unhappy 1*
`ACF(G(BK)?)Q([HIJ]LN)*(PBK|[HIJ]L)O(R|B[RED])`	*Unhappy 2*

Representation II: Tabular (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
start	q0	---	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
q0	---	xT	q1	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
q1	---	Dl	---	xL	---	P1	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
P1	---	---	---	xL	---	---	P1d	Dbrw_1	Dbcv_1	Dbbkr_1	---	---	---	---	---	---	---	---	---	xC
P1d	---	Db0_1	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	P2	---	---	xC
P2	---	---	---	xL	---	---	---	Dbrw_2	Dbcv_2	Dbbkr_2	---	---	---	---	---	P2d	---	---	---	xC
P2d	---	Db0_2	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	xT	---	xC
Dl	---	---	---	xL	xC	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
Acc1	---	Crisis1	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xT	xC
Acc2	---	Crisis2	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	xT	---	xC
Db0_1	---	---	---	xL	---	---	---	---	---	---	Nb0_1	---	---	---	---	---	---	---	---	xC
Dbcv_1	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_1	---	---	---	---	---	---	---	xC
Dbrw_1	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_1	---	---	---	---	---	---	---	xC
Dbbkr_1	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_1	---	---	---	---	---	---	---	xC
Nb0_1	---	---	---	xL	---	---	---	---	---	---	---	---	---	---	Acc1	---	P2	---	---	xC
Nbnpd_1	---	---	---	xL	---	---	---	---	---	---	---	---	---	P1	Acc1	---	---	---	---	xC
Db0_2	---	---	---	xL	---	---	---	---	---	---	Nb0_2	---	---	---	---	---	---	---	---	xC
Dbcv_2	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_2	---	---	---	---	---	---	---	xC
Dbrw_2	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_2	---	---	---	---	---	---	---	xC
Dbbkr_2	---	---	---	xL	---	---	---	---	---	---	---	Nbnpd_2	---	---	---	---	---	---	---	xC
Nb0_2	---	---	---	xL	---	---	---	---	---	---	---	---	---	---	Acc2	---	---	xT	---	xC
Nbnpd_2	---	---	---	xL	---	---	---	---	---	---	---	---	---	P2	Acc2	---	---	---	---	xC
xT	---	---	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
xL	---	---	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
xC	---	---	---	xL	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	xC
Crisis1	---	---	---	xL	xC	---	---	---	---	---	---	---	---	---	---	---	---	---	xT	xC
Crisis2	---	---	---	xL	xC	---	---	---	---	---	---	---	---	---	---	---	---	xT	---	xC

Full Transition Matrix

Implications – Complexity

- **Basic Results on Complexity**
  - DFAs enforce the Markov (or Myhill-Nerode) property – ***state is "memoryless"***
    - The DFA "lives in the moment" – all transitions are one-step-ahead actions
  - Computational complexity is manageable:
    - Constrained by the Myhill-Nerode condition
    - Measurable by the descriptional complexity of the regular expression
  - The law appears to have evolved this constraint organically
    - Sorcerer's Apprentice problem

- **Assessing Complexity**
  - The complexity of actual contracts is (in theory) rigorously measurable
  - The computational "inefficiency" of a contract is measurable:
    - Measure the contract's actual complexity, ***C***
    - Reduce the contract's DFA to its theoretical minimum and measure that complexity, ***C****
    - The difference, $\Delta C = (C - C^*)$, is a measure of "unnecessary" complexity

Next Steps - Modeling

- **Nondeterministic Finite Automata (NFAs)**
  - Standard extension of DFAs
  - Identical expressiveness, but:
    - Additional flexibility in representation
    - Therefore typically more compact

- **Transducers**
  - Extend the DFA representation to emit events
    - For example, cross-default clauses
  - Contracts that listen to other contracts
  - Systemic implications
  - Two standard cases:
    - Moore machine – Transition output event ***cannot*** depend on triggering input event
    - Mealy machine – Transition output event ***can*** depend on triggering input event

Next Steps - Empirical

- **Real Contracts**
  - International Swap Dealers Association (ISDA) – OTC swaps
  - International Foreign Exchange Master Agreement (IFEMA) – Spot FX
  - Standardizing contingency clauses
    - Work is underway on ISDA master agreements

- **Event measurement**
  - Principles for defining measurable events to support DFA representations
  - Tools for feature extraction
  - Contractual completeness (relative to the event space)
  - Contractual coherence (relative to the event space)

Gratitude

Thanks!