Lift-and-Shift: Obtaining Simulation Extractable Subversion and Updatable SNARKs Generically

Simulation extractable, subversion, and updatable NIZKs

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Introduction

Zero-knowledge Proofs

NP-language L

- Prover wants to convince verifier that some $\mathtt{x} \in L$
- Without revealing information beyond the statement $\mathtt{x} \in L$
- Define relation R_L: $\mathtt{x} \in L \Leftrightarrow \exists \mathtt{w} : (\mathtt{x}, \mathtt{w}) \in R_L$

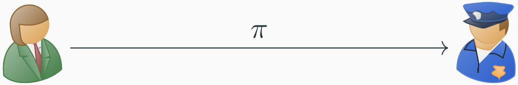
Prover $(\mathtt{x}, \mathtt{w})$

Verifier x

$\mathtt{x} \in L$ ✓

Making them Non-Interactive: ROM

Random-oracle model: Fiat-Shamir transform [FS86], Unruh transform [Unr15]

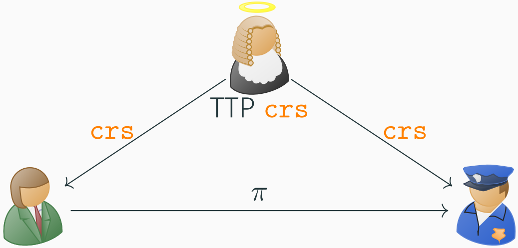


Prover $(\mathtt{x}, \mathtt{w})$ Verifier $\mathtt{x}$

$\pi \leftarrow \mathsf{Prove}_H(\mathtt{x}, \mathtt{w})$ $\mathsf{Verify}_H(\mathtt{x}, \pi) = 1 \Rightarrow \mathtt{x} \in L$

Making them Non-Interactive: CRS

Common reference string model



Prover $(\mathtt{x}, \mathtt{w})$ Verifier $\mathtt{x}$

$\pi \leftarrow \mathsf{Prove}(\mathtt{crs}, \mathtt{x}, \mathtt{w})$ $\mathsf{Verify}(\mathtt{crs}, \mathtt{x}, \pi) = 1 \Rightarrow \mathtt{x} \in L$

Important Properties

Prover cannot cheat

- Prover unable to produce valid proofs for $\mathtt{x} \notin L$

> Soundness

- Property desired by the verifier

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Verifier does not learn any information on witness $\mathtt{w}$

- Real proofs cannot be distinguished from simulated proofs
- > Zero-knowledge
- Property desired by the prover

Important Properties

Proofs of Knowledge

- Special extractor can extract witness from proofs
- Knowledge Soundness

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Proofs of Knowledge

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- › Knowledge Soundness

Strong versions

- (Knowledge) Soundness also holds if adversary can query simulated proofs
- › Simulation (knowledge) soundness
- SKS also called simulation (sound) extractability (SE)

NIZKs in the CRS Model

- Zero-knowledge contradicts extractor
- Soundness contradicts simulator

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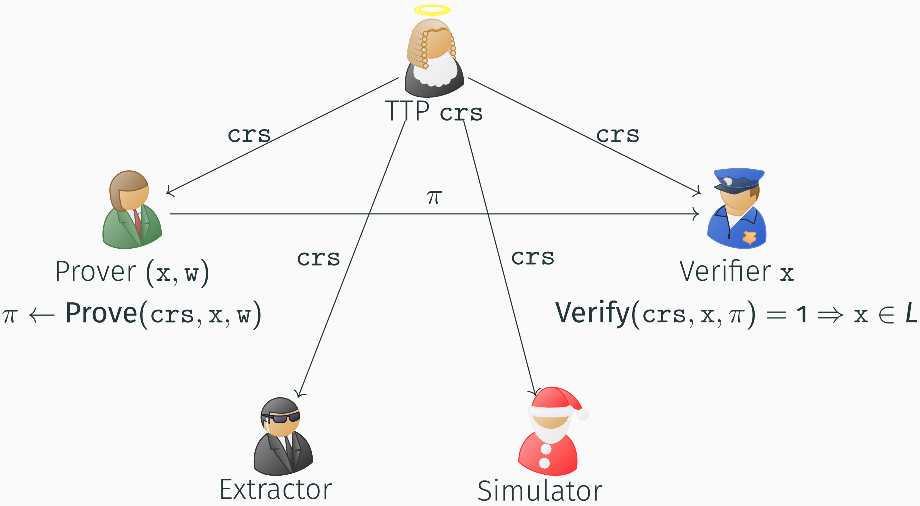
They need to have more power

- Extractor gets extraction trapdoor
- Simulator gets simulation trapdoor

NIZKs in the CRS Model



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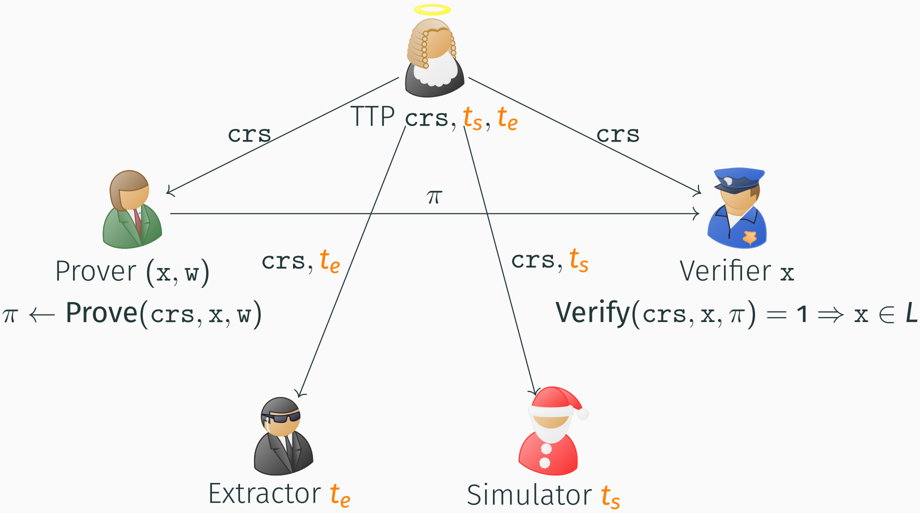

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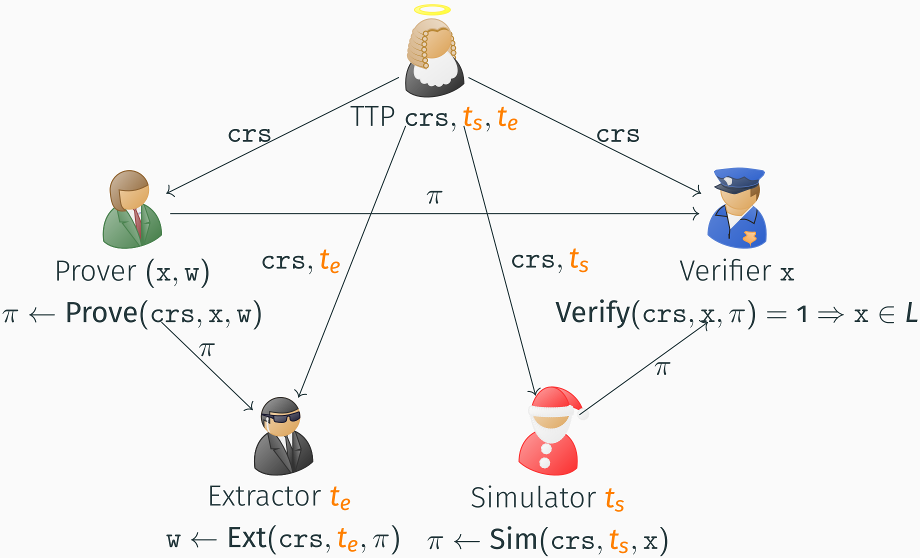

Achieving Simulation Extractability

Soundness to Knowledge Soundness

Folklore compiler [SP92]: “$\mathtt{x} \in \boldsymbol{L}$ and I have encrypted $\mathtt{w}$”

- Ω: perfectly correct IND-CPA public-key encryption
- Extend CRS with a public key of Ω: pk_Ω

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$$(\mathtt{x}, \underline{\mathtt{w}}) \in R_L \wedge \mathsf{c} = \Omega.\mathsf{Enc}(\mathsf{pk}_\Omega, \underline{\mathtt{w}}; \underline{r})$$

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- Put secret key in extraction trapdoor t_e

On Simulation Soundness

In a real world protocol:

- Adversary sees many different proofs
- Might be possible to turn proof π for word $\mathbf{x}$ into a proof $\pi' \neq \pi$
- Or worse: turn into a proof π' for a different word $\mathbf{x}' \neq \mathbf{x}$

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Hence

- Adversary may query proofs
- Must produce a proof not queried before

Similar issue for signatures: one-time EUF-CMA – EUF-CMA – strong EUF-CMA

Soundness to Simulation Soundness

Folklore compiler [GMY03; Gro06]: "$\mathtt{x} \in L$ or I know a signature under a public key in the CRS"

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- Put secret key of Σ in simulation trapdoor t_s

The C∅C∅ Framework [KZM+15]

Extend statement to

$$c = \Omega.\mathsf{Enc}(\mathsf{pk}_\Omega, \underline{\mathtt{w}}; \underline{r_1}) \wedge \big((\mathtt{x}, \underline{\mathtt{w}}) \in R_L \vee \big(\mu = f_{\underline{s}}(\mathsf{pk}_{\Sigma^1}) \wedge \rho = \mathsf{Commit}(\underline{s}; \underline{r_0})\big)\big)$$

and sign $(x, c, \mu, \pi_{L'})$ with sk_{Σ^1}

$\mathtt{crs}$ extended with ρ, pk_Ω; s, r_0 simulation trapdorr, sk_Ω extraction trapdoor

- Ω: public-key encryption
- Σ^1: strong one-time signature
- f: PRF
- Commit: Commitment

Instantation of C∅C∅

- Ω: RSA
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How to commit to the PRF key while retaining provable security?

The OC∅C∅ Framework [ARS20]

Fixed-value key-binding PRF [CMR98; Fis99]

- For a PRF f with key s and special value β, hard to find s' with $f_s(\beta) = f_{s'}(\beta)$

The OC∅C∅ Framework [ARS20]

Fixed-value key-binding PRF [CMR98; Fis99]

- For a PRF f with key s and special value β, hard to find s' with $f_s(\beta) = f_{s'}(\beta)$

Change statement to

$$(\mathtt{x}, \underline{\mathtt{w}}) \in R_L \vee \left(\mu = f_{\underline{s}}(\mathsf{pk}_{\Sigma 1}) \wedge \rho = f_{\underline{s}}(\beta)\right)$$

Instantiation of OC∅C∅

Framework	Symmetric primitive	PRF / Commitment	# of constraints
C∅C∅	SHA256	HMAC PRF + hash com.	244,992
OC∅C∅	SHA256	HMAC PRF	222,720
	SHAKE256	Sponge PRF	76,800
	MiMC-$(1025, 646)$	Sponge PRF	1,292
	GMiMC-$(1024, 4, 332)$	Sponge PRF	1,998
	Poseidon-$(1536, 2, 10, 114)$	Sponge PRF	804
	Vision-$(1778, 14, 10)$	Sponge PRF	2,800
	Rescue-$(1750, 14, 10)$	Sponge PRF	1,680
	LowMC-$(1024, 256, 1, 1027)$	Sponge PRF	4,288

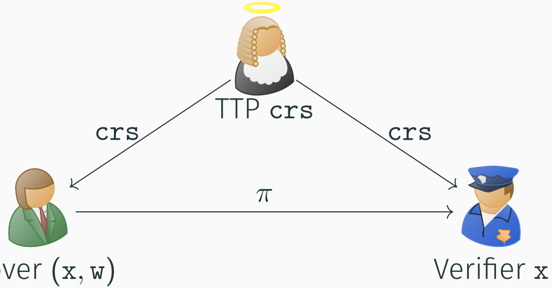
Instantiation of OC∅C∅

Beware:

- Numbers from before recent attacks appeared on ePrint
- Numbers are lower bounds assuming PRFs are fixed-value key-binding
- Alternatively: More expensive tree-based construction

Subversion and Updatability

CRS Generator



$\pi \leftarrow \textsf{Prove}(\mathtt{crs}, \mathtt{x}, \mathtt{w})$ $\qquad$ $\textsf{Verify}(\mathtt{crs}, \mathtt{x}, \pi) = 1 \Rightarrow \mathtt{x} \in L$

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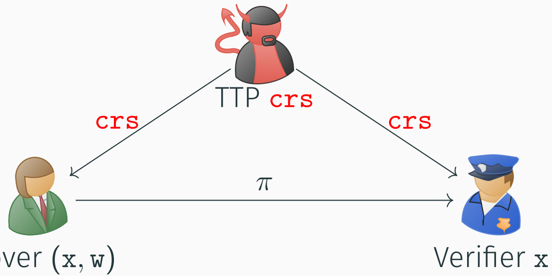

$\pi \leftarrow \mathsf{Prove}(\mathtt{crs}, \mathtt{x}, \mathtt{w})$

$\mathsf{Verify}(\mathtt{crs}, \mathtt{x}, \pi) = 1 \Rightarrow \mathtt{x} \in L$

What if the CRS generator is malicious?

Malicious CRS Generator

No guarantee that

- CRS is correct
- CRS from the correct distribution
- Trapdoors exist

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Perform CRS generation with MPC protocol

- Examples: zcash ceremony
- But in practice complicated, expensive and requires much effort beside techical realization

Subversion Resistance [BFS16]

- Subversion soundness: sound even if CRS subverted
- Subversion zero-knowledge: zero-knowledge even if CRS subverted
- Some combinations impossible

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	WI	Zero-Knowledge	Subversion ZK
Soundness	✓	✓	✓
Subversion soundness	✓	✗	✗

Constructions

Only ad-hoc constructions so far [ABL+17; Fuc18; Bag19]

General idea:

- Add public algorithm Vcrs
- If $\mathsf{Vcrs}(\mathtt{crs}) = 1$, CRS is valid and simulation trapdoor exists
- In sub-ZK proof, extract trapdoor from CRS for simulation

Updatable NIZK [GKM+18]

- Assume adversary has complete (or partial) control over $\mathtt{crs}$ generation
- Add **Ucrs** algorithm: outputs a new CRS and proof of update
- Also add **Vcrs**: verifies CRS, updates and proofs

Idea: either $\mathtt{crs}$ was generated honestly or one update was done honestly

- Verifier updates CRS to ensure soundness
- Prover updates CRS to ensure zero-knowledge

Lamassu [ARS20]

Generic framework to obtain

- subversion or updatable
- and simulation extractable zk-SNARKs

Built from

- updatable signatures
- alternative compiler for simulation soundess [DS19]

Key-homomorphic Signatures

- Homomoprhism between private-key and public-key spaces: $\mu\colon S \to P$
  Natural in the DLOG setting: $x \mapsto g^x$
- Signatures can be adapted from pk to $\mathsf{pk}' = \mathsf{pk} \cdot \mu(\mathsf{sk}' - \mathsf{sk})$ if $\mathsf{sk}' - \mathsf{sk}$ known
- Examples: Schnorr, BLS, and many more

Simulation Soundness using Key-Homomorphic Signatures

Compiler [DS19]:

- Σ: key-homormorphic EUF-CMA signature scheme
- Σ^1: one-time signature scheme
- Extend CRS with a public key of Σ: pk
- For a proof
  - Generate key pairs $(\mathsf{sk}', \mathsf{pk}')$ for Σ and $(\mathsf{sk}^1, \mathsf{pk}^1)$ for Σ^1
  - Extend statement to

$$(\mathtt{x}, \mathtt{w}) \in R_L \vee \mathsf{pk}' = \mathsf{pk} \cdot \mu(\mathsf{sk}' - \underline{\mathsf{sk}})$$

  - Sign pk^1 with sk' and sign the proof with sk^1
- Put secret key of Σ in simulation trapdoor t_s

Obtain simulation extractable, subversion zk-SNARK

Updatable Signatures

Similar to updatable CRS

- **Upk**: update **pk** and provide proof of update
- **Vpk**: verify update

Idea: either original **pk** created honestly or update was done honestly

Example: Schnorr in bilinear groups with BDH knowledge assumption

Obtain simulation extractable, updatable zk-SNARK

Comparison of SE SNARKs

	Gen.	Sub.	Upd.	crs	π
CØCØ [KZM+15]	✓	✓	✗	1κ	$2\mathbb{Z}_N, 1\kappa$
OCØCØ[G]	✓	✓	✗	2κ	$3\mathbb{G}, 3\mathbb{Z}_q, 1\kappa$
LAMASSU[S,G]	✓	✓	✗	$1\mathbb{G}$	$4\mathbb{G}, 5\mathbb{Z}_q$
LAMASSU[S,G]	✓	✓	✓	$1\mathbb{G}_1, 1\mathbb{G}_2$	$1\mathbb{G}_1, 1\mathbb{G}_2, 3\mathbb{G}, 5\mathbb{Z}_q$
LAMASSU[S,BB]	✓	✓	✗	$1\mathbb{G}$	$1\mathbb{G}_1, 1\mathbb{G}_2, 1\mathbb{G}, 2\mathbb{Z}_q$
LAMASSU[S,BB]	✓	✓	✓	$1\mathbb{G}_1, 1\mathbb{G}_2$	$2\mathbb{G}_1, 2\mathbb{G}_2, 2\mathbb{Z}_q$
Groth-Maller [GM17]	✗	✗	✗	$(2n+5)\mathbb{G}_1, n\mathbb{G}_2$	–
Bowe-Gabizon [BG18]	✗	✗	✗	–	$1\mathbb{G}_1, 1\mathbb{G}_2$
Lipmaa (S^{se}_{qap}) [Lip19]	✗	✓	✗	$n\mathbb{G}_1$	$1\mathbb{G}_1$
Kim-Lee-Oh [KLO19]	✗	✓	✓	$n\mathbb{G}_1$	–
Atapoor-Baghery [AB19]	✗	✗	✗	1κ	$1\mathbb{G}_1, 1\mathbb{G}_2, 1\kappa$
Baghery [Bag19]	✗	✓	✗	1κ	$1\mathbb{G}_1, 1\mathbb{G}_2, 1\kappa$

Conclusion

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CØCØ, OCØCØ:

- CØCØ hard to instantiate correctly and efficiently
- Even if commitment with enough structure used, CØCØ does not seem to yield updatability
- sub-ZK SE SNARK if underlying SNARK already sub-ZK
- OCØCØ gives another application of fixed-value key-binding PRFs

LAMASSU:

- generic sub-ZK, updatable SE SNARK
- Open problems: key-homomorphic / updatable signatures from lattices, ...

Questions?

Preprint: `https://eprint.iacr.org/2020/062.pdf`

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References

References i

[AB19] S. Atapoor and K. Baghery. Simulation extractability in groth's zk-snark. In *DPM/CBT@ESORICS*, volume 11737 of *LNCS*, pages 336–354. Springer, 2019.

[ABL+17] B. Abdolmaleki, K. Baghery, H. Lipmaa, and M. Zajac. A subversion-resistant SNARK. In *ASIACRYPT (3)*, volume 10626 of *LNCS*, pages 3–33. Springer, 2017.

[ARS20] B. Abdolmaleki, S. Ramacher, and D. Slamanig. Lift-and-shift: obtaining simulation extractable subversion and updatable snarks generically. Cryptology ePrint Archive, Report 2020/062, 2020. `https://eprint.iacr.org/2020/062`.

References ii

[Bag19] K. Baghery. Subversion-resistant simulation (knowledge) sound nizks. In *IMACC*, volume 11929 of *LNCS*, pages 42–63. Springer, 2019.

[BB04] D. Boneh and X. Boyen. Short signatures without random oracles. In *EUROCRYPT*, volume 3027 of *LNCS*, pages 56–73. Springer, 2004.

[BFS16] M. Bellare, G. Fuchsbauer, and A. Scafuro. Nizks with an untrusted CRS: security in the face of parameter subversion. In *ASIACRYPT (2)*, volume 10032 of *LNCS*, pages 777–804, 2016.

[BG18] S. Bowe and A. Gabizon. Making groth's zk-snark simulation extractable in the random oracle model. Cryptology ePrint Archive, Report 2018/187, 2018. `https://eprint.iacr.org/2018/187`.

References iii

[CMR98] R. Canetti, D. Micciancio, and O. Reingold. Perfectly one-way probabilistic hash functions (preliminary version). In *STOC*, pages 131–140. ACM, 1998.

[DS19] D. Derler and D. Slamanig. Key-homomorphic signatures: definitions and applications to multiparty signatures and non-interactive zero-knowledge. *Des. Codes Cryptogr.*, 87(6):1373–1413, 2019.

[Fis99] M. Fischlin. Pseudorandom function tribe ensembles based on one-way permutations: improvements and applications. In *EUROCRYPT*, volume 1592 of *LNCS*, pages 432–445. Springer, 1999.

[FS86] A. Fiat and A. Shamir. How to prove yourself: practical solutions to identification and signature problems. In *CRYPTO*, volume 263 of *LNCS*, pages 186–194. Springer, 1986.

[Fuc18] G. Fuchsbauer. Subversion-zero-knowledge snarks. In *PKC (1)*, volume 10769 of *LNCS*, pages 315–347. Springer, 2018.

[GKM+18] J. Groth, M. Kohlweiss, M. Maller, S. Meiklejohn, and I. Miers. Updatable and universal common reference strings with applications to zk-snarks. In *CRYPTO (3)*, volume 10993 of *LNCS*, pages 698–728. Springer, 2018.

[GM17] J. Groth and M. Maller. Snarky signatures: minimal signatures of knowledge from simulation-extractable snarks. In *CRYPTO (2)*, volume 10402 of *LNCS*, pages 581–612. Springer, 2017.

[GMY03] J. A. Garay, P. D. MacKenzie, and K. Yang. Strengthening zero-knowledge protocols using signatures. In *EUROCRYPT*, volume 2656 of *LNCS*, pages 177–194. Springer, 2003.

[Gro06] J. Groth. Simulation-sound NIZK proofs for a practical language and constant size group signatures. In *ASIACRYPT*, volume 4284 of *LNCS*, pages 444–459. Springer, 2006.

[KLO19] J. Kim, J. Lee, and H. Oh. Updatable crs simulation-extractable zk-snarks with a single verification. Cryptology ePrint Archive, Report 2019/586, 2019. `https://eprint.iacr.org/2019/586`.

[KZM+15] A. Kosba, Z. Zhao, A. Miller, Y. Qian, H. Chan, C. Papamanthou, R. Pass, abhi shelat, and E. Shi. Coco: a framework for building composable zero-knowledge proofs. Cryptology ePrint Archive, Report 2015/1093, 2015. `https://eprint.iacr.org/2015/1093`.

[Lip19] H. Lipmaa. Simulation-extractable snarks revisited. Cryptology ePrint Archive, Report 2019/612, 2019. `https://eprint.iacr.org/2019/612`.

[SP92] A. D. Santis and G. Persiano. Zero-knowledge proofs of knowledge without interaction (extended abstract). In *FOCS*, pages 427–436. IEEE Computer Society, 1992.

[Unr15] D. Unruh. Non-interactive zero-knowledge proofs in the quantum random oracle model. In *EUROCRYPT (2)*, volume 9057 of *LNCS*, pages 755–784. Springer, 2015.