It's Not What It Looks Like: Manipulating Perceptual Hashing based Applications
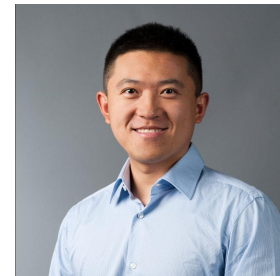
CCS 2021

Qingying Hao
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Virginia Tech

Gang Wang
UIUC

Perceptual Hashing

- Generate fingerprints for images

(a) "e2a43f415352c3f5"

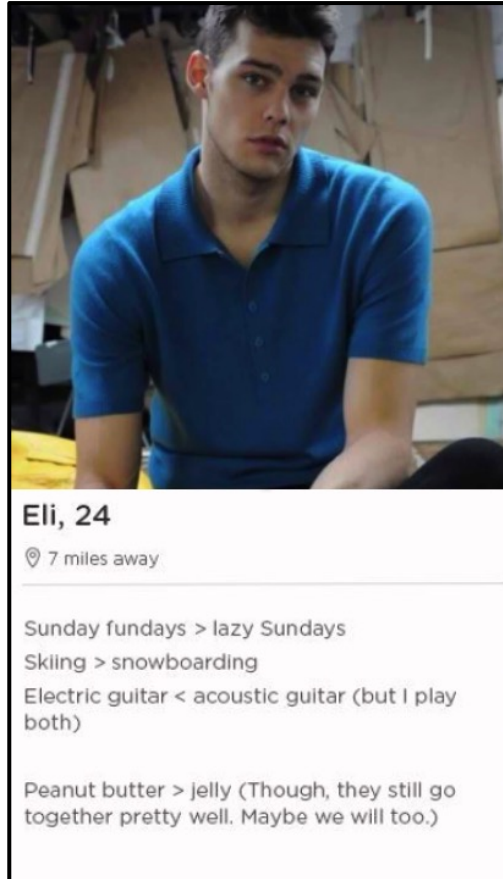(b) "e2a43f415352c3f5"

Hamming Distance = 0

(c) "fc231cf82376b90c"

Hamming Distance = 32

Perceptual Hashing for Reverse Image Search
Catfishing / Dating Scam Detection

Perceptual Hashing for Misinformaiton Detection

Original image → Semantic → **Edited image**
Changes
Xo **Xm**

Pages that include matching images

www.snopes.com › Fact Checks › Fauxtography ▾

Does This Photograph Show Stacey Abrams Touting the ...

797 × 980 · Nov 6, 2018 — A photograph of Georgia gubernatorial candidate **Stacey Abrams** posing with Linda Sarsour (a Palestinian-American **Muslim** political activist) ...

www.washingtonexaminer.com › weekly-standard › fac... ▾

Fact Check: Did the Muslim Brotherhood Show Support for ...

998 × 954 · Oct 17, 2018 — A photo of activist Linda Sarsour and Georgia candidate for governor **Stacey Abrams** ... over the ...

twitter.com › staceyabrams › status ▾

Stacey Abrams على تويتر: "Pr...

1591 × 2048 · Jan 20, 2018 @womensmarch national c... women speak up, ... When
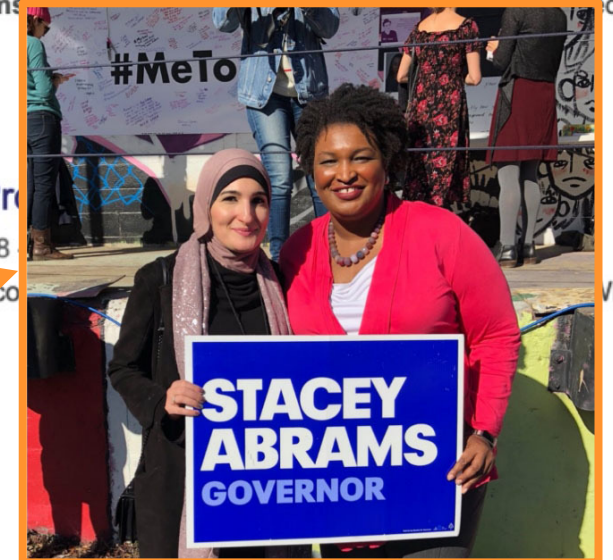
What if the Attacker Can Do More

Attack image

X_a

Pages that include matching images

www.ajc.com › blog › politics › out-state-political-forces-...

National forces help shape Georgia governor's race

1080 × 1080 · May 14, 2018 — **Kamala Harris** to ... ge about **Stacey Abrams**: "Make sure she wins." Th ... appearance ...

twitter.com › staceyabrams › status ▾

Stacey Abrams on Twitter: "Humbled to ha...

1080 × 1080 · May 11, 2018 — Humbled to have ... as we fight to build a Georgia where everyone ha ... thrive.

www.facebook.com › stacey.abrams.77 › posts › it-was-... ▾

Stacey Abrams - It was a pleasure to host Sen. Kamala ...

898 × 960 — **Kamala Harris** yesterday in Atlanta during our "Drive to History." Sen. Harris' commitment to public education, criminal justice reform and social justice makes her a ...

This Paper.

- Primary goal:
  - Generate attack images to subvert perceptual hashing based image search
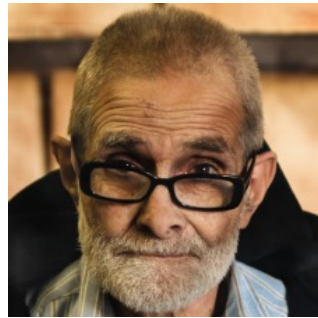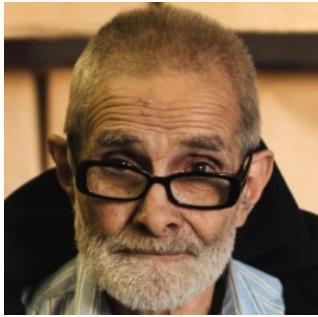
Original image **X$_o$**   Attack image **X$_a$**

Look similar   **+**   **Have different perceptual hash values**

Attack effect: searching the attack image will no longer return the source!

- Secondary goal: theme here . Textbox a little bit left
  - Blackbox model
  - Robust against practical defenses

Background: pHash Algorithms

- Standard process:

| Input | Reduce size (e.g., 32*32) Reduce color | Compute **DCT** frequency | Reduce **DCT** matrix (e.g., 8*8), Compute median | Frequency comparison |

64-bit binary hash string

DCT: Discrete Cosine Transform
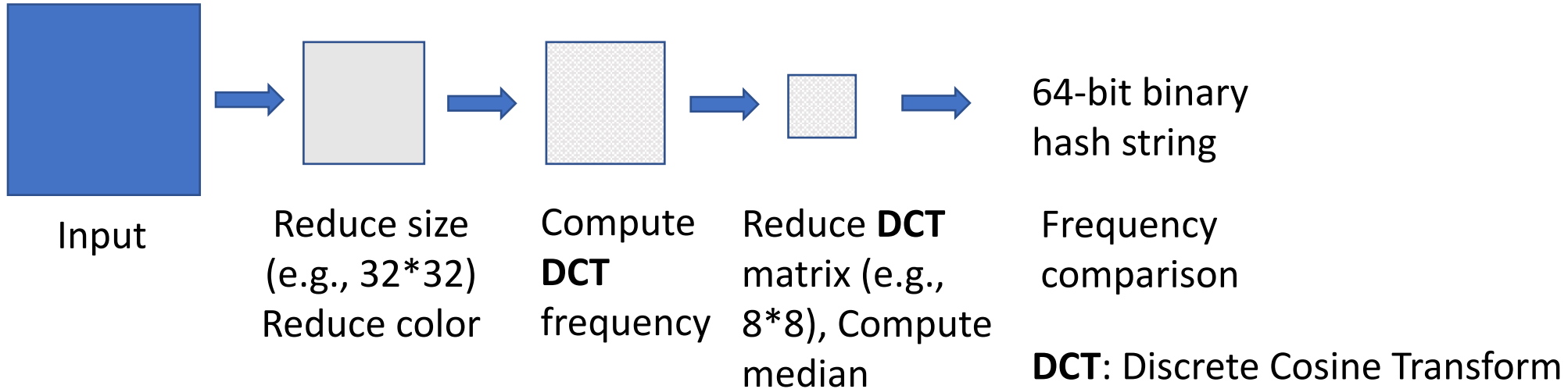
- Challenges:
  - pHash is not diffentiable
  - Design a function to approximate pHash process and estimate the gradient

Our Attack Algorithm

$$\underset{\boldsymbol{x_a}}{\text{minimize}} \quad \mathrm{D}(\boldsymbol{x_a}, \boldsymbol{x_o}) + c \cdot f(\boldsymbol{x_a}, \boldsymbol{x_o})$$

Visual difference   Similarity in hash space

X_a: The attack image

X_o: The original image

- L_2 Distance
- Structural Similarity Index Measure(SSIM)
- **Learned Perceptual Image Patch Similarity (LPIPS)**

$$f(\boldsymbol{x_a}, \boldsymbol{x_o}) = \max\{\tanh(1 - |H(\boldsymbol{x_a}) - H(\boldsymbol{x_o})|/d_t), 0\},$$

Hamming Distance (normalized)

Targted Hamming Distance threshold (normalized)

For a 64-bit hash string, if the attacker aims to cause 20-bit difference between x_a and x_o, targeted d_t=20/64=0.3125
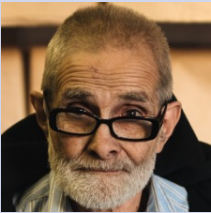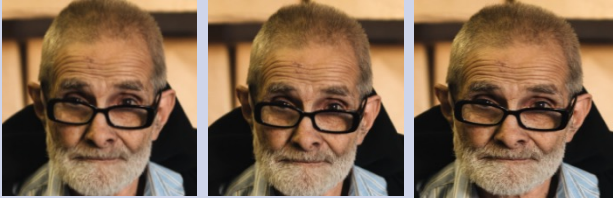
Our Attack Framework: Basic Attack

- **Grayscale initialization**

RGB image → Graysclae image → **Grayscale Initialization** (Noises learned) → RGB Attack (Model converted)

Noise applied
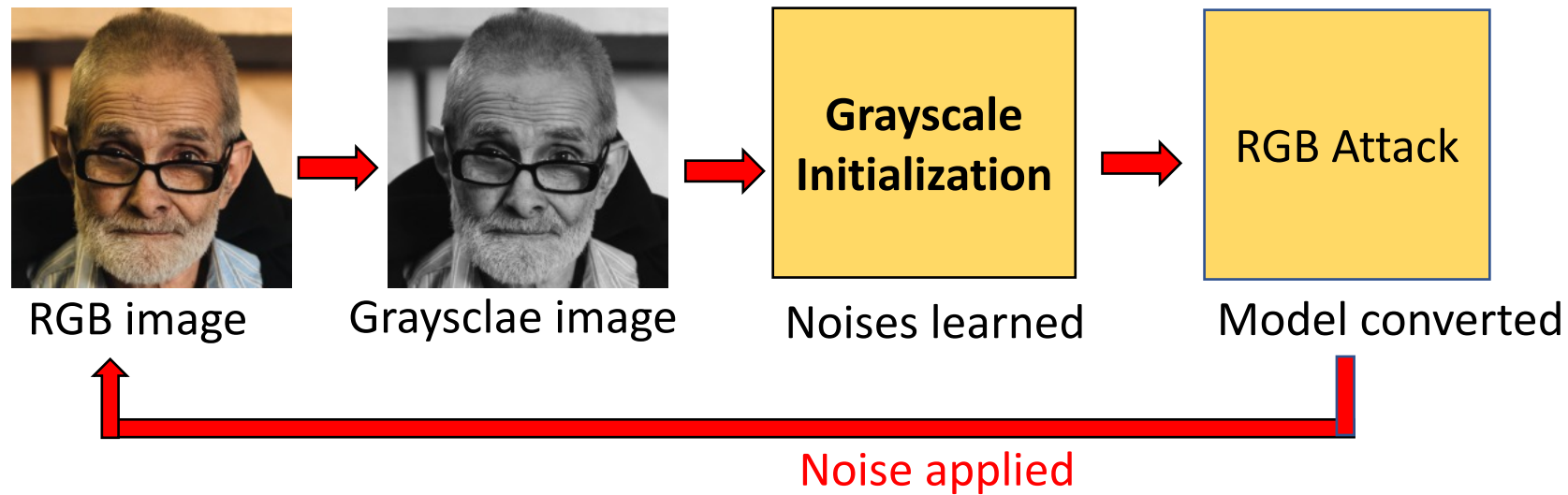
- Attacking grayscale image **will reduce** the attack search space
- Standard perceptual hashing algorithms calculate hash codes based on grayscale images

Our Attack Framework: Advanced Attacks

Idea	Detailed methods
Attack over Input Ensemble (AoE) Motivation: search engines may have processed the original images	$$\min_{x_a} D(x_a, x_o) + c \cdot (f(x_a, x_o) + \sum_{t \in T} f(x_a, t(x_o)))$$ **X$_a$** differs from **X$_o$** and slightly **transformed** set of **t(x$_o$)** with at least **d$_t$** Cropped Rotated Disproportionate Scaled

Experiments Setups

- Datasets
  - ImageNet
    - 1.28 million images
  - Face Images – Catfishing / social network impersonation detection
    - 1,081 images
  - Image Manipulation Dataset (IMD) - Misinformation detection
    - ~ 2400 images

- Target perceptual hashing algorithms
  - Standard pHash
  - Blockhash (Block Mean Value Based Hash)
    - Slice the image into blocks
    - Each bit is calculated for one block by comparing it with neighboring blocks

Emulate Image Reverse Search

Send query attack image

**ImageNet + Face dataset
1.28 million images**

"d4927970c2cd7b51"

"9beac122bdb2b0a3"

Pick distance **threshold** τ,
return all images whose hash Hamming
Distance Difference <= τ

"ed929b64699a9295"

Backend Database (pHash)
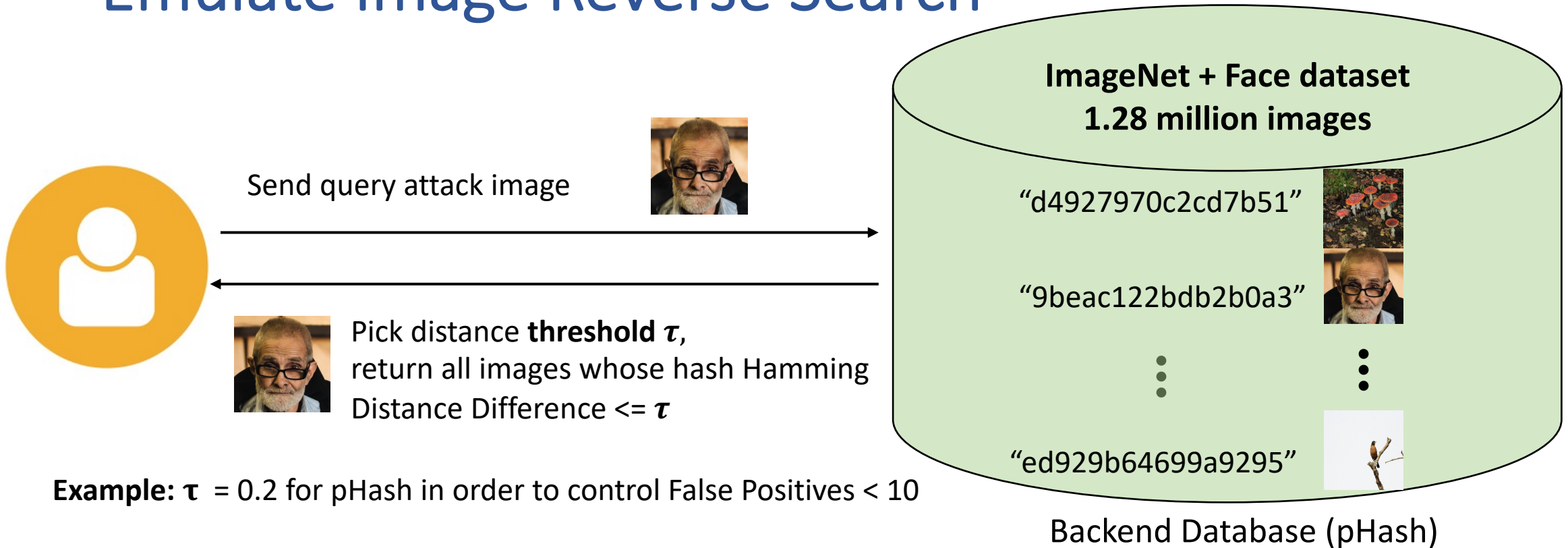
Example: τ = 0.2 for pHash in order to control False Positives < 10

Search Evaluation Metrics	Explanation
Average false positives (**FP**)	Average number of returned irrelevant images
Top-K Hit Rate (**Top-K HR**)	True match images are among top-k returned images
Failed Query Rate (**FQR**)	True match images are not in returned images

Impact of Grayscale Initialization

Efficiency of grayscale initialization VS. direct RGB attack

Method	Target hash distance $d_t = 0.15$		
	Hash Distance	Perceptual Diff. (**LPIPS**)	Num of Iterations*
Direct RGB (Baseline)	0.153	0.039	198.52
Grayscale + RGB (Our)	0.156	0.005	22.98 + 1.52 = 24.5

Basic attacks against pHash using 50 images from ImageNet

Num of Iterations*: number of iterations to find the (first) targeted attack image

Basic Attack Standard pHash

Highly successful attack

Dataset	Target hash distance d_t = 0.31				
	Hash Dist	Perceptual Diff.	#FP	Top-5 HR	FQR
ImageNet	0.310	0.034	3.38	0%	100%
Face	0.293	0.050	3.32	6%	94%

τ = 0.2 for phHash in order to control FP of the search engine < 10

Clean	LPIPS=0.0004	LPIPS=0.004	LPIPS=0.030
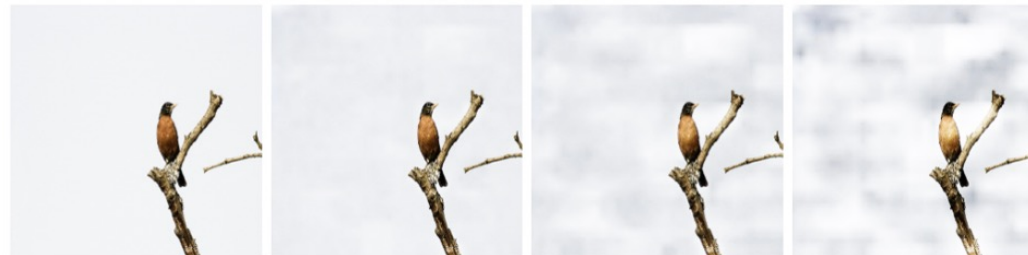
Clean	LPIPS=0.015	LPIPS=0.097	LPIPS=0.185

Basic Attack Blockhash

Dataset	Target hash distance $d_t = 0.31$				
	Hash Dist	Perceptual Diff.	#FP	Top-5 HR	FQR
ImageNet	0.314	0.049	0	0%	100%
Face	0.313	0.119	0	0%	100%

Highly successful attack

$\tau = 0.14$ for Blockhash in order to control FP of the search engine < 10

Clean $d_t = 0.15$ $d_t = 0.31$
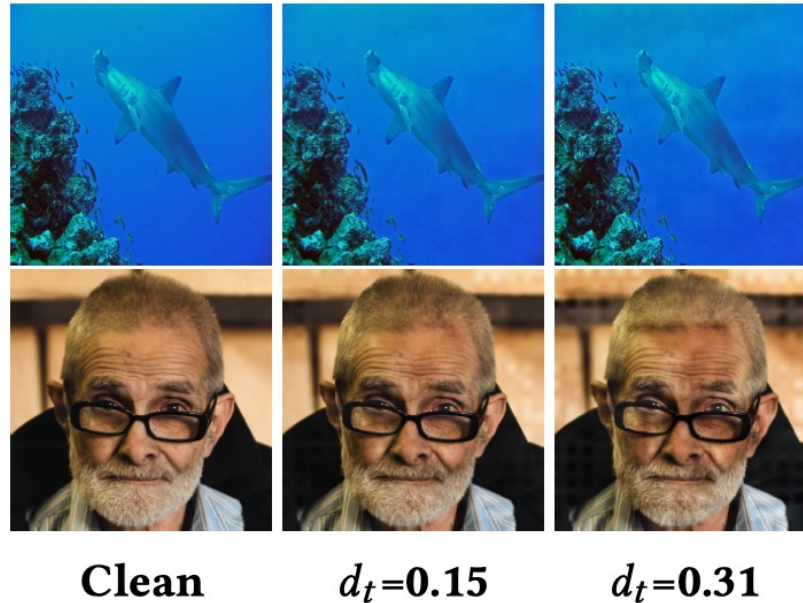
Advanced Attack Results
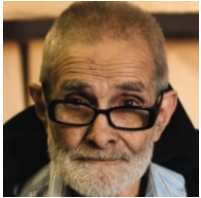
Cropping (t1)
Remove **2.5%** edge of the image
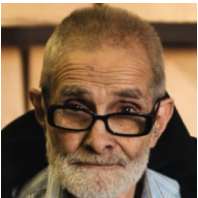
Rotation (t2)
Rotate an image by a **small** angle and central crop the image.
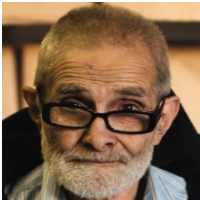
Disproportionate Scaling (t3)
Slightly stretch the image by increasing the width to **w (scaling factor, e.g., 1.1)** times the original width. Crop the image.

Attack Method	Blockhash, Target hash distance d_t = 0.15	
	Hash Dist	Perceptual Diff.
AoE	0.15	0.049
AoT1	0.150	0.122
AoT2	0.160	0.164
AoT3	0.155	0.122

Advanced attacks against Blockhash using 50 images from Face dataset
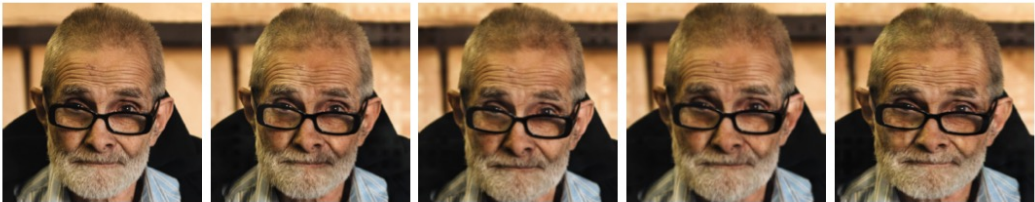
Clean AoE AoT1 AoT2 AoT3

Example images for the advanced attacks against Blockhash with target hash distance d_t =0.15

Real World Experiments

TinEye　　Google Images　　Yandex　　Microsoft Bing

- Real-world search engines return multiple versions of the images
  - Need to manually examine the results to calculate true/false positives

- Procedure:
  - Small scale
    - Run multiple algorithms on 5 random images
    - Pick the strongest attack
  - Large scale evaluation

Real World Experiments: Tineye Search

Real World Experiments: Large Scale

- Pick the best attack algorithm (AoT3 Disproportionate Scaling pHash)
- Test on 50 images from the Face dataset
  - Slightly tune up targeted hash distance d_t from 0.31 to 0.34
  - Increase the disproportionate scaling factor from 1.1 to 1.24

Evaluation Metrics	Tineye	Google	Bing	Yandex
Avg. Reduction Rate*	100%	88%	100%	-1364%
Top1 Hit Rate	100% -> 0%	88% -> 36%	34% -> 0%	82% -> 58%
Top10 Hit Rate	100% -> 0%	96% -> 36%	34% -> 0%	86% -> 58%
False Postive Rate*	0% ->100%	11% -> 66%	66% -> 100%	21% -> 90%

Avg. (Average) Reduction Rate*: The rate of returned results reduction
False Positive Rate*: The rate of irrelevant images among all returned results

Real-world Attack Case Study

(a) Original Image

(b) Cropped Image to Spread Misinfo
"A Pennsylvania elections worker actually filling out ballots rather than counting them"

Google: 160 matched
TinEye: 4 matched

Google: 11 matched
TinEye: 0 matched

(c) Attack Image

Google: 0 matched
TinEye: 0 matched

(d) Attack Image
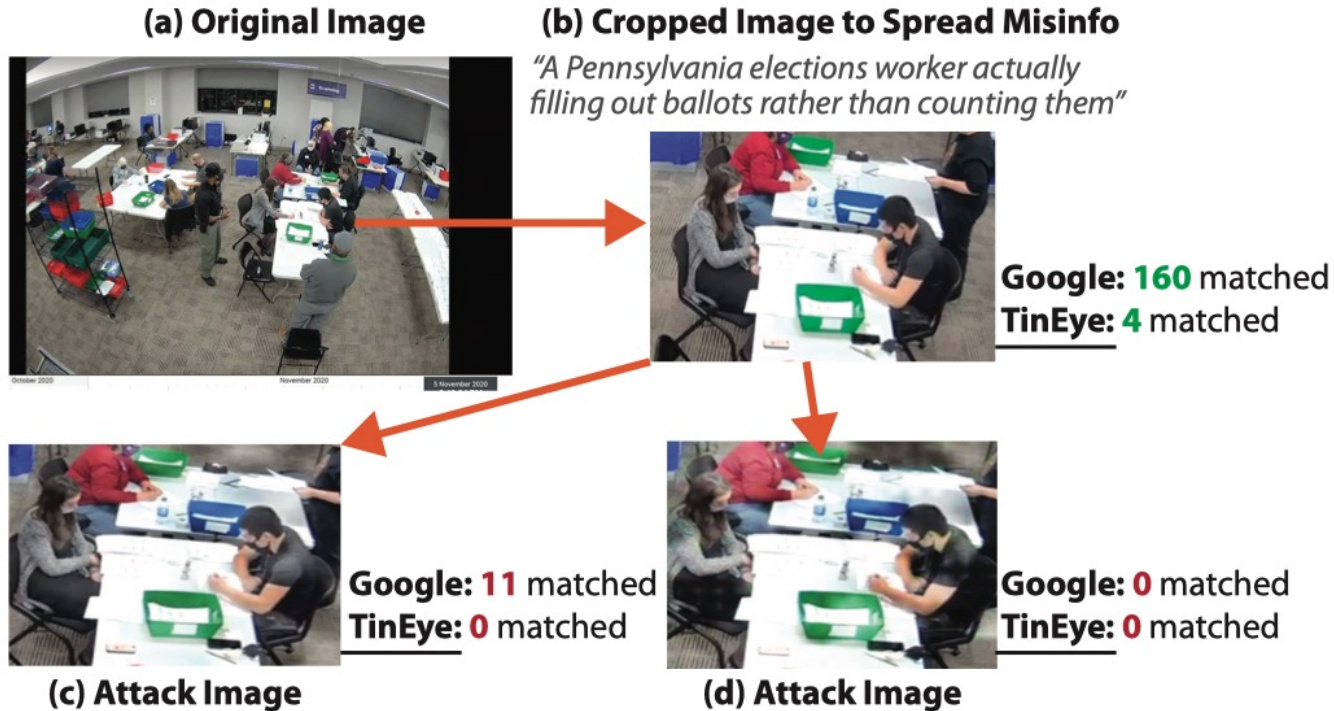
November 6, 2020 presidential election

(a) **Original**: a ballot counter was transcribing ballots that had been damaged

(b) **Cropped** image : the election worker is filling out the ballot
- Can still find the original / source image
- Show in fact-checking websites

(c) **Attack** image:
- AoT3-pHash

(d) **Attack** image
- AoT3-Blockhash

Potential Defense

Defense

Server-side Robust pHash

Hash Ensemble:
The server uses pHash, Blockhash, aHash, dHash and wHash

Adaptive
Attack
Works!

User-side Robust Search

Browser Extension:
Preprocess the images before the search
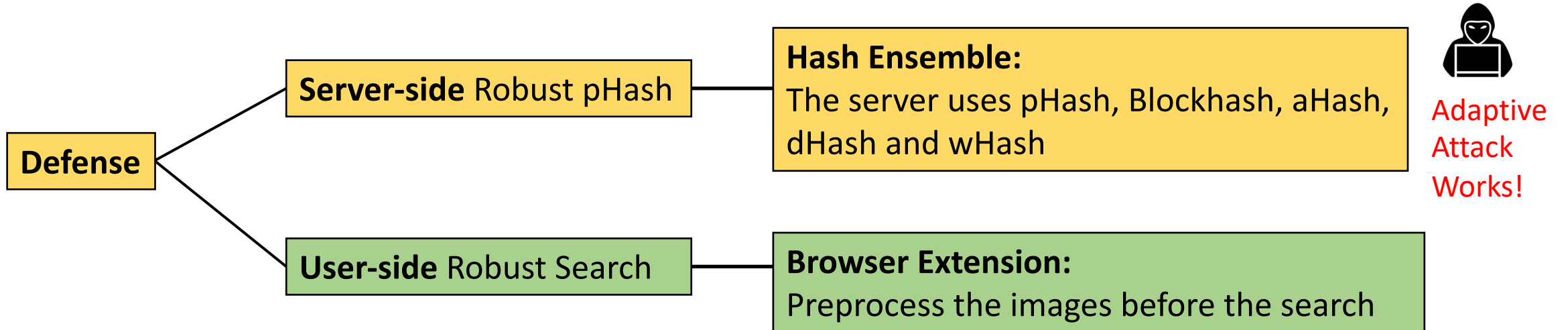
Dataset	Hash Distance Target Dist d_t=0.31						Perp. Dist	Searching Results		
	pHash	Blockhash	aHash	dHash	wHash			#FP	Top-5 HR	FQR
ImageNet	0.368	0.327	0.366	0.438	0.386	0.109		2.88	0%	100%
Face	0.371	0.317	0.354	0.421	0.375	0.146		3.38	0%	100%

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Potential Defense

Defense

Server-side Robust pHash

Hash Ensemble:
The server uses pHash, Blockhash, aHash, dHash and wHash

User-side Robust Search

Browser Extension:
Preprocess the images before the search
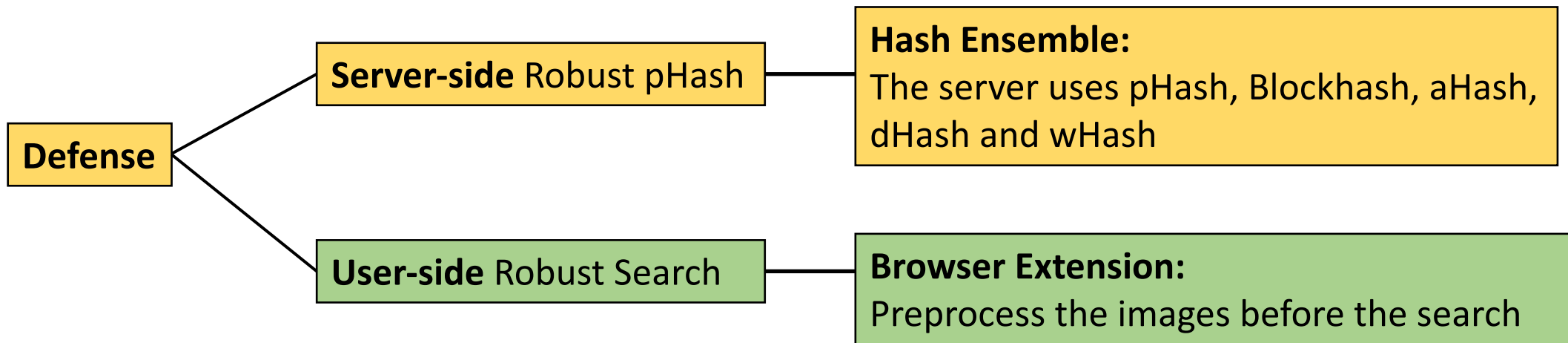
- Generate a set of search images using randomized transformations
  - Rotation, scaling, denoise and image filters
  - Parameters are randomized
- The search engine could fuse the results for all transformed images
  - Improve the top-1 and top-10 hit rates while reducing false positives

Conclusions and Future Directions

- In Conclusion:
  - Design new attacks against perceptual hashing based applications in a black-box manner
  - Evaluate our attack against the standard and robust perceptual hashing algorithms
  - Test our attack using real-world image search engines
- Future:
  - To evaluate other security sensitive areas (e.g., child pornography content detection)
  - Experiment with more robust defense methods
  - Understand vulnerabilities of deep learning based hash functions

Thank You

https://qingyinghao.web.illinois.edu

Question list:

Backup slides Start here

Attack Effects on Online Abuse Detection Systems

$\mathbf{X_o}$ → Semantic Altering → $\mathbf{X_m}$ → PHash Attack → $\mathbf{X_a}$

Original Image → Edited Image → Attack Image
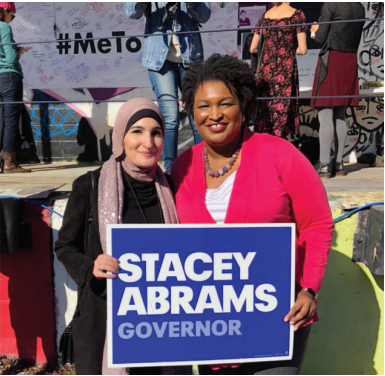
+1 example,as
Animation!

Pages that include matching images

www.snopes.com › Fact Checks › Fauxtography ▼
Does This Photograph Show Stacey Abrams Touting the ...
797 × 980 · Nov 6, 2018 — A photograph of Georgia gubernatorial candidate Stacey Abrams posing with Linda Sarsour (a Palestinian-American Muslim political activist) ...

www.washingtonexaminer.com › weekly-standard › fac... ▼
Fact Check: Did the Muslim Brotherhood Show Support for ...
998 × 954 · Oct 17, 2018 — A photo of activist Linda Sarsour and Georgia candidate for governor Stacey Abrams holding up a campaign sign together was posted over the ...

twitter.com › staceyabrams › status ▼
Stacey Abrams على تويتر: "Proud to stand with activist ...
1591 × 2048 · Jan 20, 2018 — Proud to stand with activist, organizer and @womensmarch national co-chair @lsarsour during #WomensMarch2018. When women speak up, ...

Pages that include matching images

www.ajc.com › blog › politics › out-state-political-forces-... ▼
National forces help shape Georgia governor's race
1080 × 1080 · May 14, 2018 — Kamala Harris took the stage with a simple message about Stacey Abrams: "Make sure she win... appearance ...

twitter.com › staceyabrams › status ▼
Stacey Abrams on Twitter: "Humbled t...
1080 × 1080 · May 11, 2018 — Humbled to... as we fight to build a Georgia where everyo... thrive.

www.facebook.com › stacey.abrams.77 › posts › it-was-...
Stacey Abrams - It was a pleasure to h...
898 × 960 — Kamala Harris yesterday in Atlanta during our "Drive to History." Sen. Harris' commitment to public education, criminal justice reform and social justice makes her a ...

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Existing Attacks and Limitations

- Introduce image distortions to alter the semantic meaning of the image[1 – old days].
  - Maintain same(similar) hash values
  - Target at image authentication applications

- Most existing attacks noises are manually crafted[2]

(a) original (b) object change
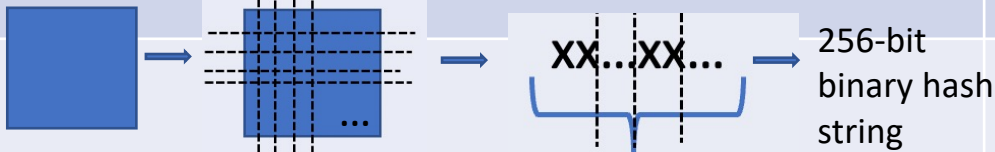
(c) object removal (d) object insertion

Targeted Perceptual hashing algorithms (backup)

- Attack two types of perceptual hashing algorithms. Show examples. Real images

Hash Algorithms	Process		Variations
pHash (standard)	Input / Reduce size (e.g., 32*32) Reduce color / Compute DCT* / Reduce DCT* (e.g., 8*8), Compute median / Frequency comparison / 64-bit binary hash string		aHash (average hash), dHash (difference Hash), wHash(Wavelet Hash)
	First few slides?		
Blockhash (robust)	Input / Slice into blocks (e.g., 16*16 = 256 blocks), Block = sum of image pixel values / Divide blocks into groups(4), Calculate median / Compare pixel values with each group mean / 256-bit binary hash string		

DCT*: Discrete Cosine Transformation (Frequency calculation method)

Compare Advanced and Basic Attacks: Transferability

Attack Method	Transferred Distance (target hash dist $d_t = 0.31$)				
	pHash	Blockhash	aHash	dHash	wHash
pHash Basic	**0.313**	0.122	0.073	0.164	0.081
pHash AoE	**0.324**	0.158	0.105	0.215	0.109
pHash AoT3	**0.246**	0.163	0.100	0.200	0.103

Attack Method	Transferred # FP (target hash dist $d_t = 0.31$)				
	pHash	Blockhash	aHash	dHash	wHash
pHash Basic	**3.38**	2.6	74.12	15.34	22.66
pHash AoE	**2.64**	1.82	80.74	9.28	12.44
pHash AoT3	**3.2**	1.48	130.54	12.4	14.08

Attack Method	Transferred Top-5 HR (target hash dist $d_t = 0.31$)				
	pHash	Blockhash	aHash	dHash	wHash
pHash Basic	**0%**	68%	36%	46%	30%
pHash AoE	**0%**	36%	20%	24%	8%
pHash AoT3	**10%**	28%	16%	24%	12%

Attack Method	Transferred FQR (target hash dist $d_t = 0.31$)				
	pHash	Blockhash	aHash	dHash	wHash
pHash Basic	**100%**	32%	58%	54%	66%
pHash AoE	**100%**	64%	78%	76%	90%
pHash AoT3	**88%**	72%	78%	74%	84%

Transfer the attack image optimized for pHash to other hash functions using ImageNet dataset

- Advanced attacks (AoE, AoT3) are more transferable than the basic attack.
- AoE is three times slower than AoT3, so AoT3 is a better option

Real-world Attack Case Study

(a) Original Image

(b) Cropped Image to Spread Misinfo

"A Pennsylvania elections worker actually filling out ballots rather than counting them"

Google: 160 matched
TinEye: 4 matched

(c) Attack Image

Google: 11 matched
TinEye: 0 matched

(d) Attack Image

Google: 0 matched
TinEye: 0 matched

Ad frauds detection

Image Authentication

Phishing webpages detection [CCS19...]

Technical support scams

Online survey scams

Misinformation Campaign

Counterfeits Apps UI Detection

TinEye

Digital Forensics

Identity impersonation Detection

Reverse Image Search

Google Images

Pornography content detection

Microsoft Bing

Yandex

32
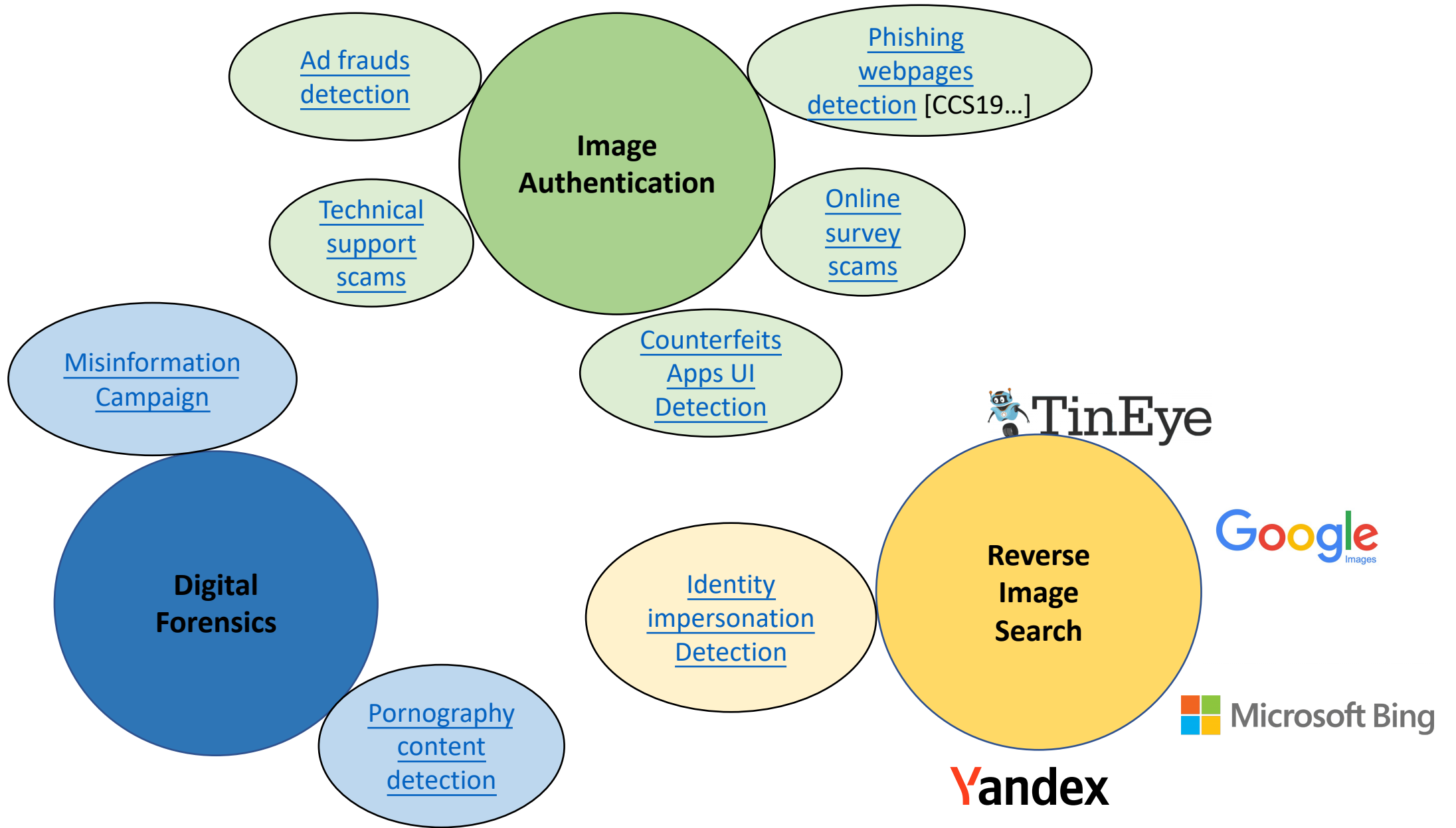
Basic Attack Standard pHash: design choices

- Randomly select 50 images for **ImageNet**

- Impact of perceptual distance function:

Distance Function	Target hash distance d_t=0.15				Target hash distance d_t=0.31			
	Hash Dist.	L_2	Pdist	# Iterations (Gray+RGB)	Hash Dist.	L_2	Pdist	# Iterations (Gray+RGB)
L2 as $D()$	0.156	25.306	0.033	90.42+13.18	0.292	50.449	0.116	278.54+149.86
LPIPS as $D()$	0.156	6.788	0.005	22.98+1.52	0.310	20.828	0.034	87.56+1.40

Comparison of different perceptual distance functions using the basic attack (ImageNet)

- Impact of Grayscale Initialization

Method	Target hash distance d_t=0.15		
	Hash Dist	Pdist	# Iterations
Direct RGB (Baseline)	0.153	0.039	198.52
Grayscale+RGB (Our)	0.156	0.005	22.98+1.52

Comparison of direct optimizing RGB images vs. using grayscale initialization (ImageNet)

Dataset	Target hash distance $d_t=0.15$					Target hash distance $d_t=0.31$					Target hash distance $d_t=0.47$				
	Hash Dist	Pdist	# FP	Top-5 HR	FQR	Hash Dist	Pdist	# FP	Top-5 HR	FQR	Hash Dist	Pdist	# FP	Top-5 HR	FQR
ImageNet	0.156	0.005	6.72	96%	0%	0.310	0.034	3.38	0%	100%	0.441	0.120	1.68	0%	100%
Face	0.156	0.009	4.76	100%	0%	0.293	0.050	3.32	6%	94%	0.383	0.145	2.90	4%	96%

Clean   LPIPS=0.0004   LPIPS=0.004   LPIPS=0.030

Clean   LPIPS=0.015 $d_t=0.15$ LPIPS=0.097 $d_t=0.31$ LPIPS=0.185 $d_t=0.47$

- τ = 0.2 (Search engine distance threshold)
- When d_t=0.15 and 0.31, most images can reach the targeted hash distance
- Near 100% FQR and top-5 HR is no more than 6%
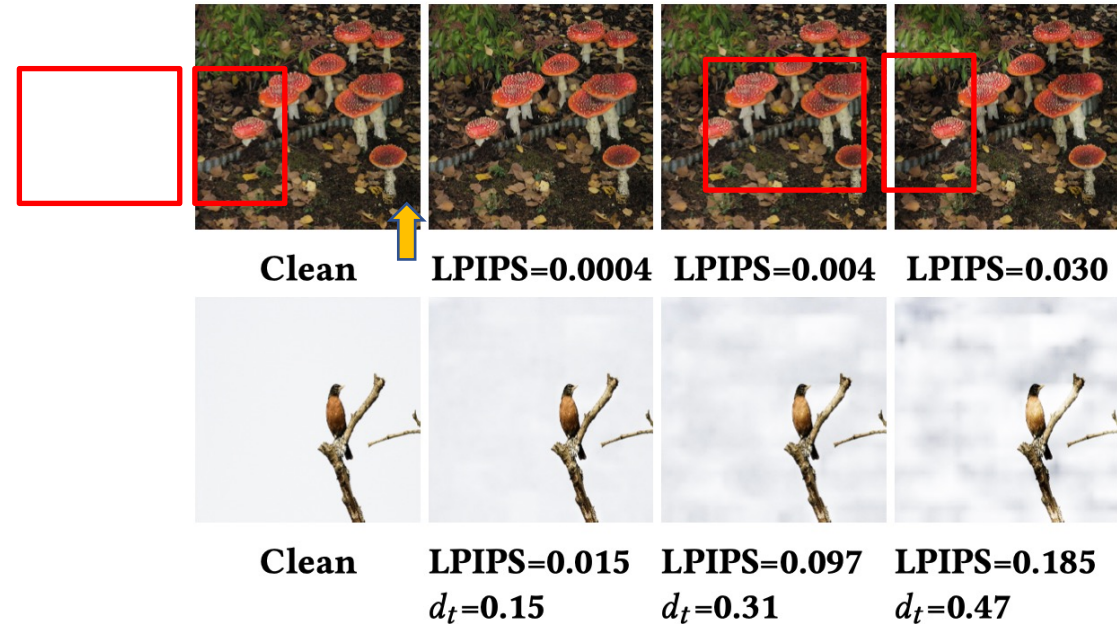
Dataset	Target hash distance d_t = 0.31				
	Hash Dist	Perceptual Dist.	#FP	Top-5 HR	FQR
ImageNet	0.310	0.034	3.38	0%	100%
Face	0.293	0.050	3.32	6%	94%

Attack Evaluation using IMD Dataset

- IMD (Image Manipulation Dataset) dataset
  - Over 50% pairs have a distance below 0.2
    - Easy to trace the manipulated image
  - Create x_a based on x_m (modified version) to further increase hash distance

Attack Method	Target Hash Dist d_t = 0.31	
	Hash Dist	Pdist
pHash Basic	0.30	0.027
pHash AoT3	0.244	0.146

Basic attack and AoT3 Disproportionate Scaling attack using IMD dataset

Clean   Manipulated   Basic   AoT3

Pages that include matching images

www.brylin.com › programs-services › mental-health-tr... ▾

Mental Health Treatment for Children and Adolescents ...
1920 × 1280 — Mental health treatment program for children and adolescents at BryLin offers assessment, crisis stabilization and treatment for kids 5-17 years of age.

www.fay3.com › ...   ▾ Translate this page

صور لـ #شخص #مشاعر #مراهق #صورة #صبي #طفل - موقع فايع
375 × 250 — Adolescent #Portrait #Person #Child #Feelings # **Boy** .

menteor-organizzarea.com › hankou...   ▾ Translate this page

【子供反抗期】10歳からの対応の仕方!子供との関係性は ...
800 × 533 · May 9, 2019 — 子供の反抗期。最近では特に低年齢化しているともいわれていますが、こればかりは親として見守ることなどして対応していくしかないです ...

tarbiazakia.com › 2018/05 › هذا-ماسيم...   ▾ Translate this page

هذا ما يعلمه الأهل الناجحون لأولادهم قبل عمر 18 سنة – التربية الذكية
الهم : المصروف يجب أن لا يكون فقط من أجل "المتعة". الأولوية يجب أن تكون لمراقبة — 1024 × 1024 كيفية إنفاق هذا المال. علّموا أولادكم أن لا يشتروا كيفما كان، وأن يوزعوا مصاريفهم ...

Previous   1

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640 × 640 — new piercing : flat, helix and upperlobe Each body is unique and healing times vary ...

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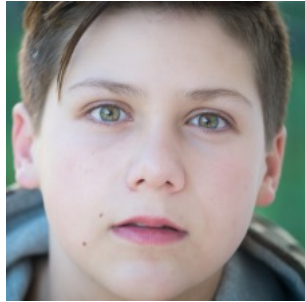**Carine Llamas Psychanalyste - Psychanalyste Enfants ...**
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Rhône-Alpes s'est déroulée le 24 janvier ...

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しているともいわれていますが、これ
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を使い始めて 3ヶ月になりました。最近、顎に大きなニキビが.

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