

Timeliner

“Tipped Off by Your Memory Allocator”:
Device-Wide User Activity Sequencing from
Android Memory Images

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Importance of a Timeline



Crime Scene Reconstruction

"involves evaluating the context of a scene and the physical evidence found there in an effort to identify what occurred and in what order it occurred."

Importance of a Timeline



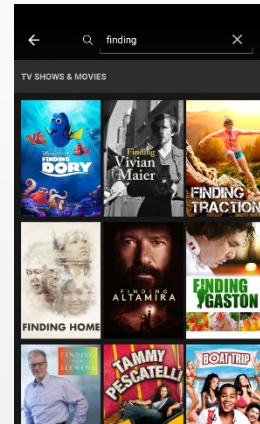
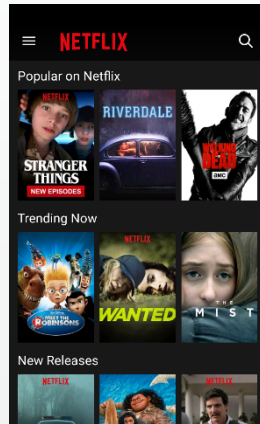
App Specific Logs

Coarse Grained Actions

Not a Device-Wide Timeline

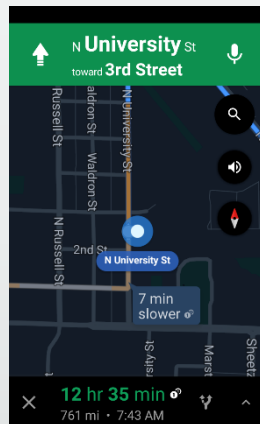
Importance of a Device-Wide Timeline

Netflix



Cyber crimes typically involve a variety of mobile apps, with complex sequencing of user-actions

Maps



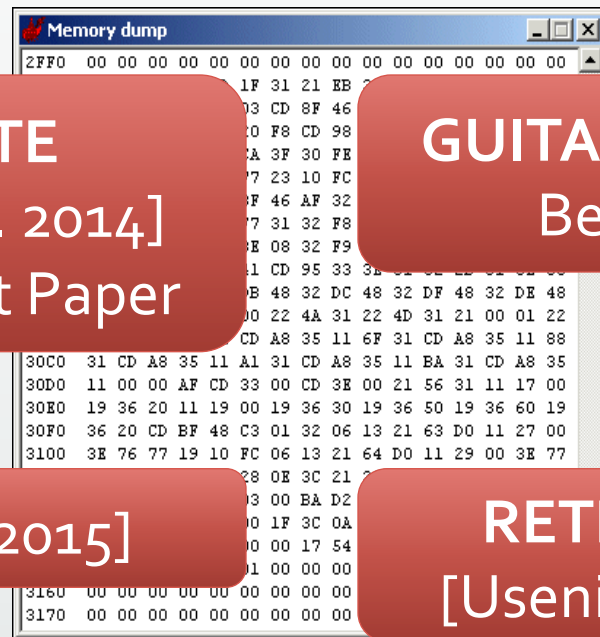
What if apps were ~~NOT~~ **POSSIBLY**—
Distracted Driving

Need a Device-Wide solution to recover past user-actions that is not influenceable by the device-owner

Memory Forensics

Persistent storage is not enough to re-sequence a device-wide timeline

Timeliner complements existing memory forensic techniques



DSCRETE
[Usenix Sec. 2014]
Best Student Paper

GUITAR [CCS 2015]
Best Paper

VCR [CCS 2015]

RETROSCOPE
[Usenix Sec. 2016]

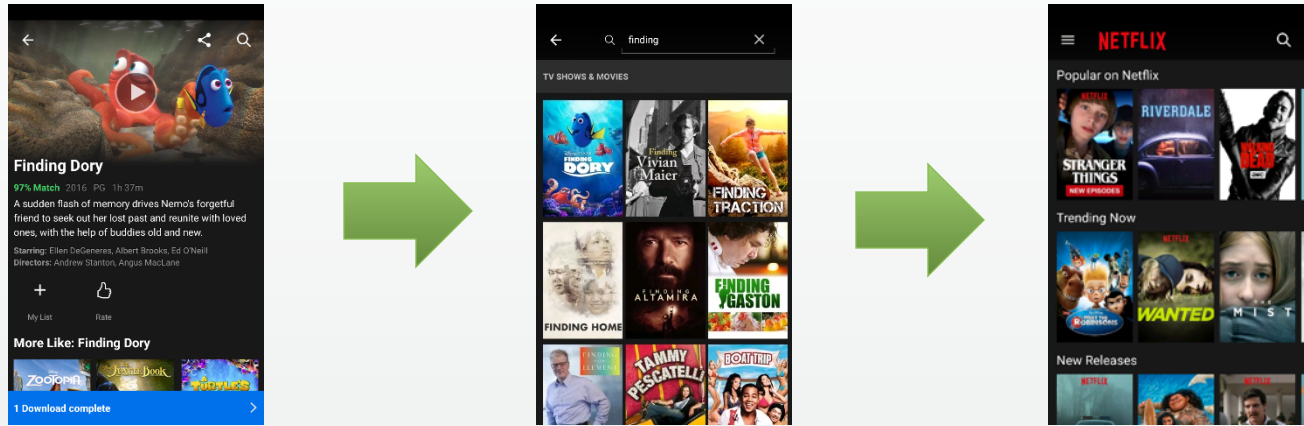
Activities As User-Actions

WhatsApp	VoipActivity	RecordAudio	CameraActivity
Signal	ConversationList	Conversation	ShareActivity
Dialer	InCallActivity	CallLogActivity	CallDetailActivity
Chase	AccountsActivity	TransferActivity	QuickDepositStart
Netflix	HomeActivity	SearchActivity	MovieDetails

Activities are Android abstractions for a “single, focused thing a user can do”

Some Applications and a Few Example Activities

Activities As User-Actions



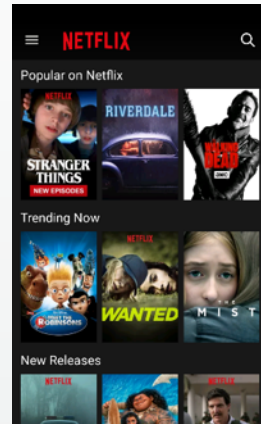
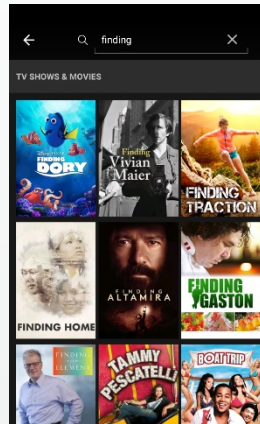
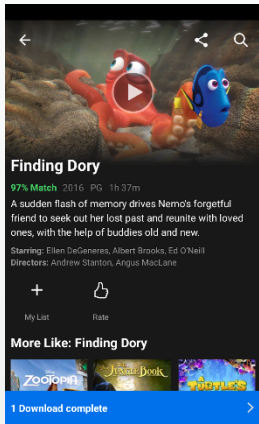
Activities are Android abstractions for a “single, focused thing a user can do”

Apps
Android

Activity Lifecycle handled by ActivityManagerService which provides device-wide supervision



Activity Stack As A Solution?



No ordering available between different Activity Stacks

Apps

Android

DialContactsActivity

Dialer

MovieDetailsActivity

SearchActivity

HomeActivity

Netflix (Current)

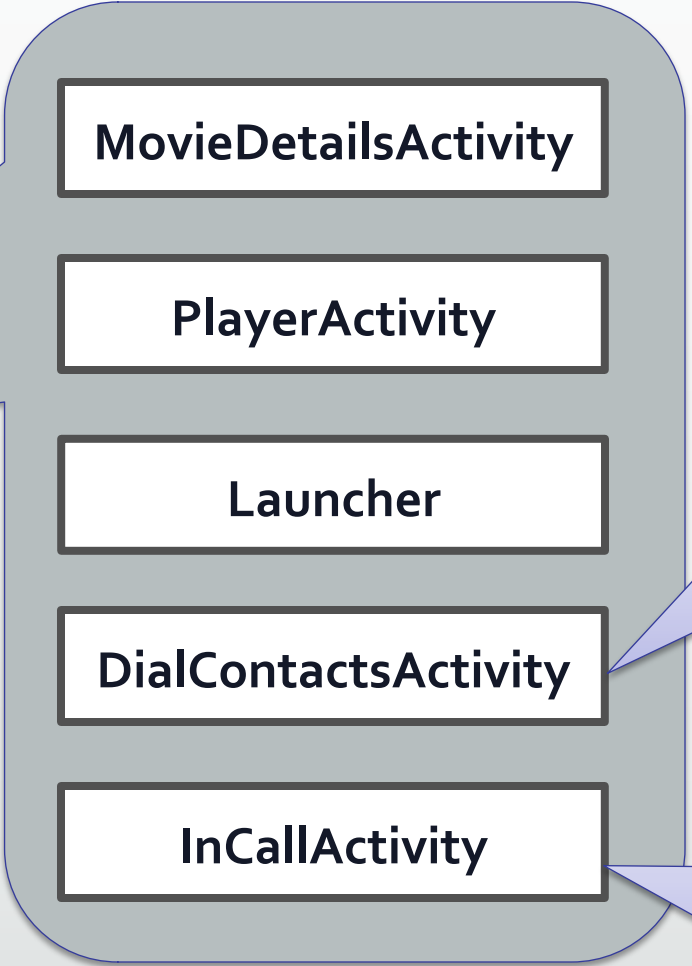
Activity Stacks contain the current state, and not the past state – which is what we want

Timeliner

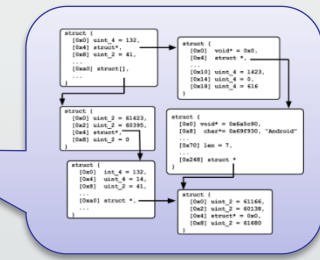
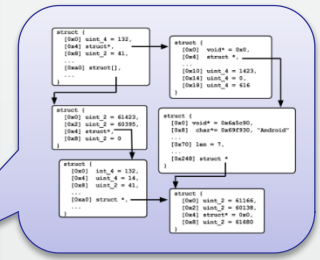
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3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
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3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
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30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
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30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
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3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8B 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
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Timeliner

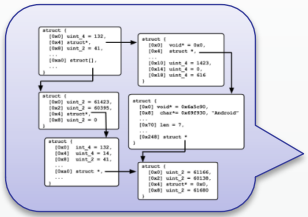
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3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
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3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2E 31 3E 08
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30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
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3140 3C 8B 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
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3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



Timeliner recovers Activities using key self-identifying data structures

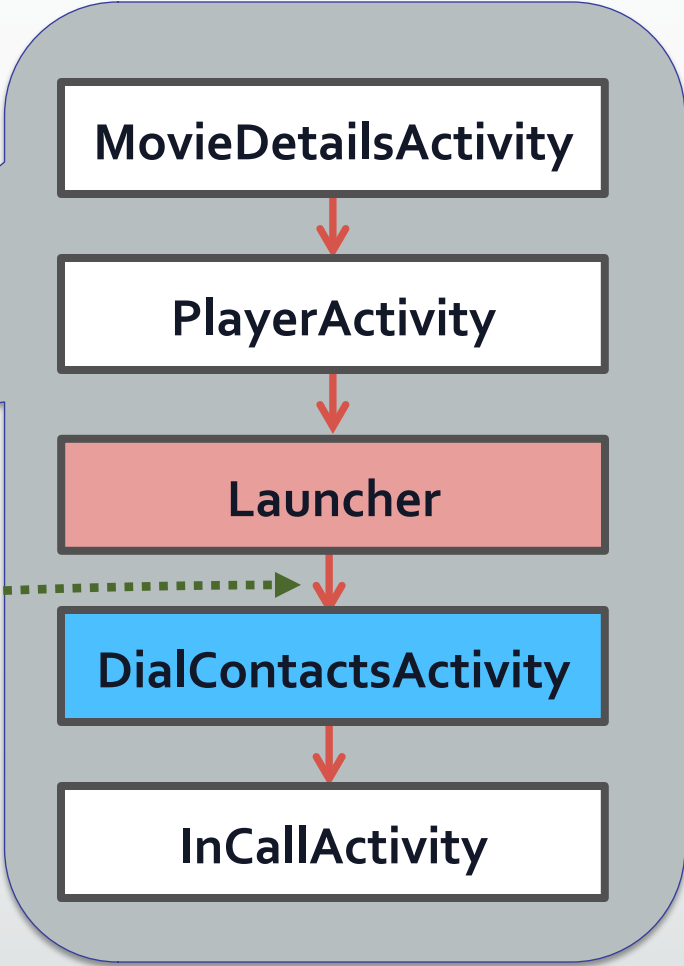
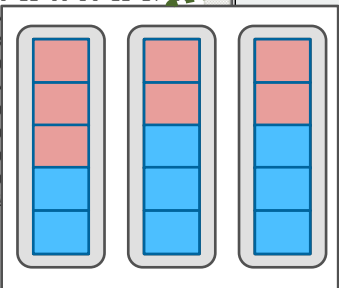


Timeliner



Memory dump

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3010	21	00	50	11	F0	03	CD	8F	46	21	00	58	11	FF	07	36			
3020	70	23	1B	7B	B2	20	F8	CD	98	46	CD	B9	46	CD	3E	00			
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3040	BE	AF	21	2C	31	77	23	10	FC	3E	18	32	FE	31	21	50			
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3070	CB	52	22	27	31	3E	08	32	F9	31	CD	8D	47	00					
3080	32	DE	31	CD	52	41	CD	95	33	3E	01	32	2E	31	3E	08			
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3100	3E	76	77	19	10	FC	06	13	21	63	D0	11	27	00					
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Timeliner recovers Activities using key self-identifying data structures

Infer ordering based on allocated locations in memory

Residual Data Structures

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
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3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
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30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
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3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8B 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
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```

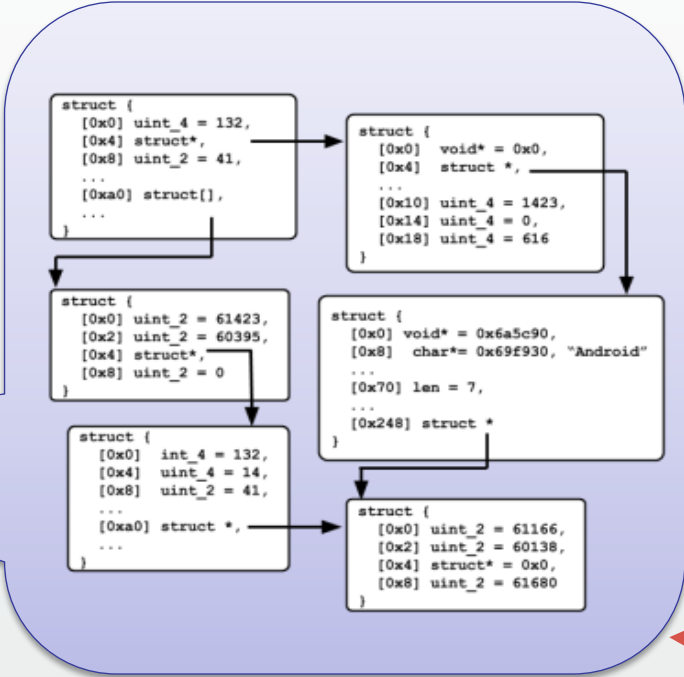
MovieDetailsActivity



Activity Manager Service

Residual Data Structures

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
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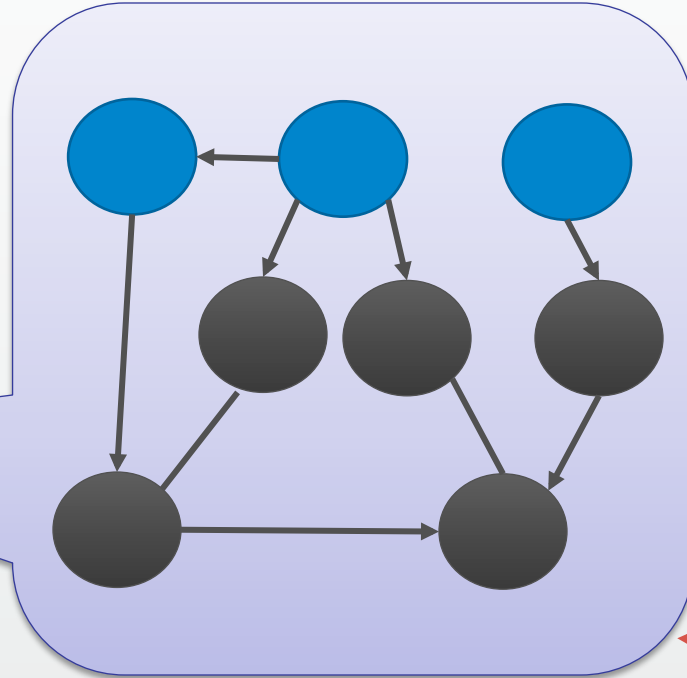
MovieDetailsActivity



Activity Manager Service

Residual Data Structures

```
Memory dump
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MovieDetailsActivity



Apps

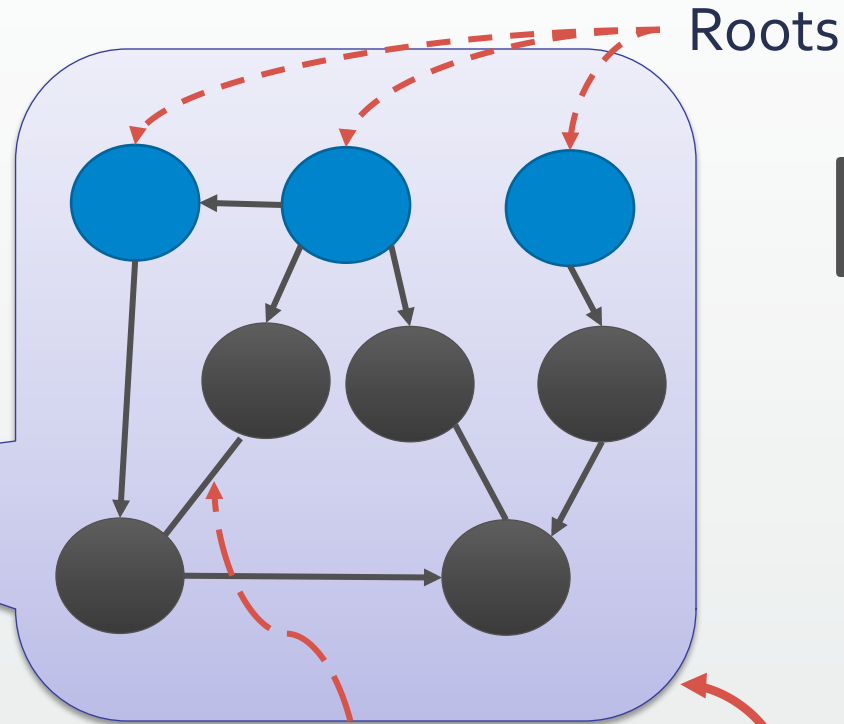
Android

Activity Manager Service

Residual Data Structures

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Memory dump
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```



Field/Value Matches

MovieDetailsActivity



Apps

Android

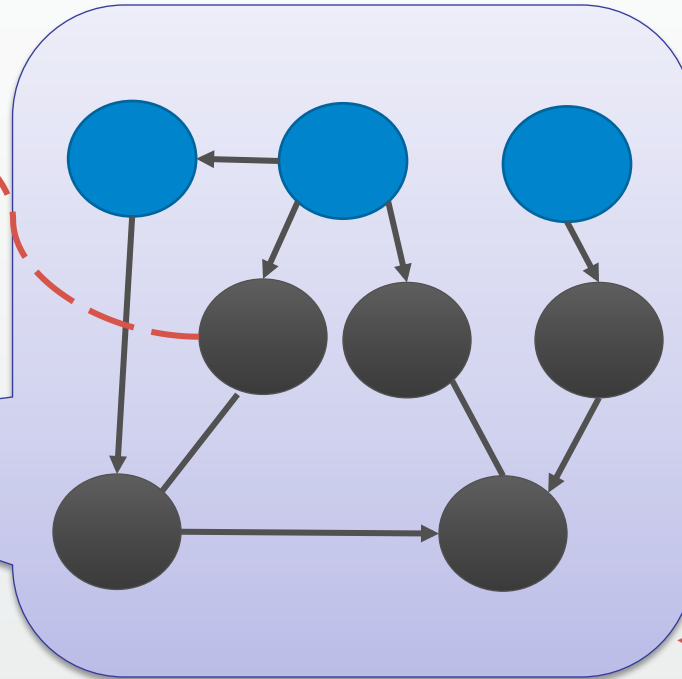


Activity Manager Service

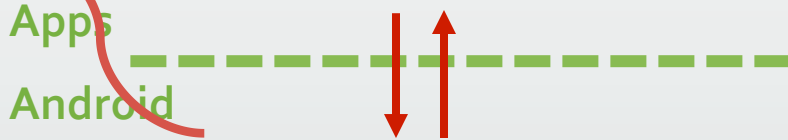
Residual Data Structures

netflix.ui.MovieDetailsActivity

```
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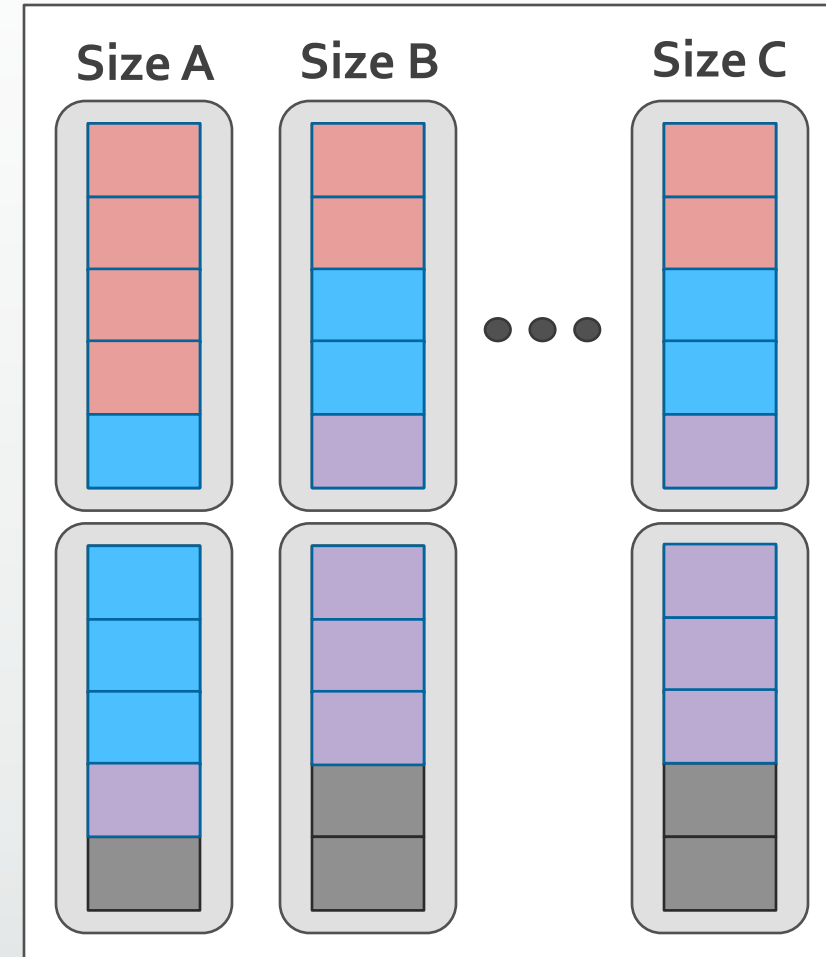
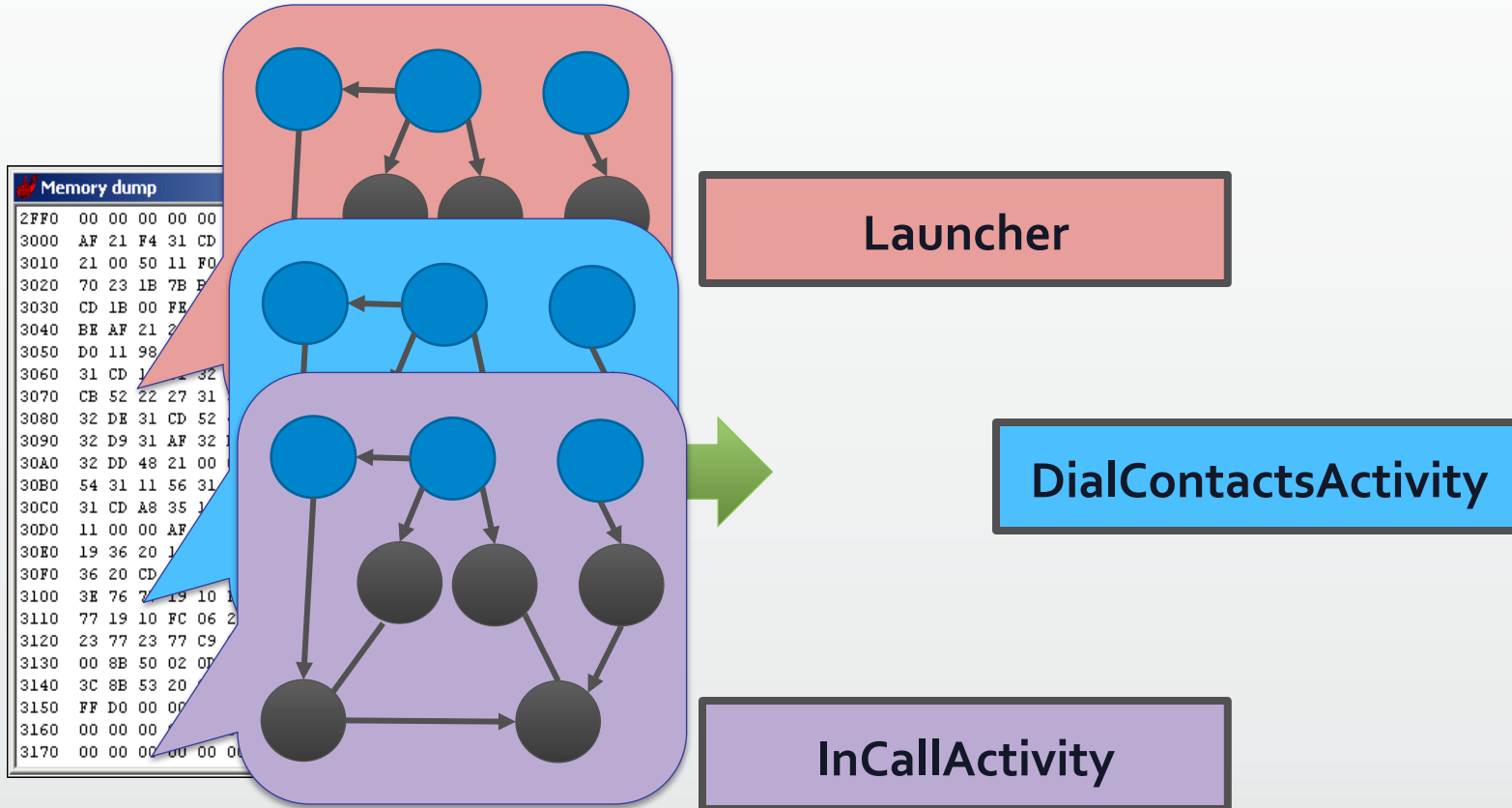


MovieDetailsActivity



Activity Manager Service

"First-Available" Allocation

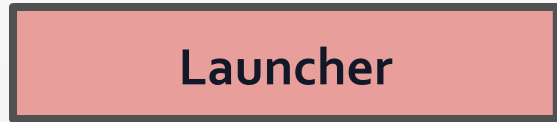


Memory Allocator

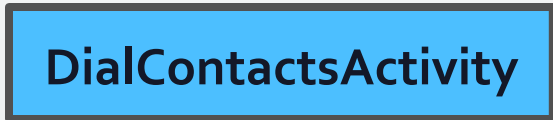
Temporal Ordering From Spatial Ordering

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Memory dump
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3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
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3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
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30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
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30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 02 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

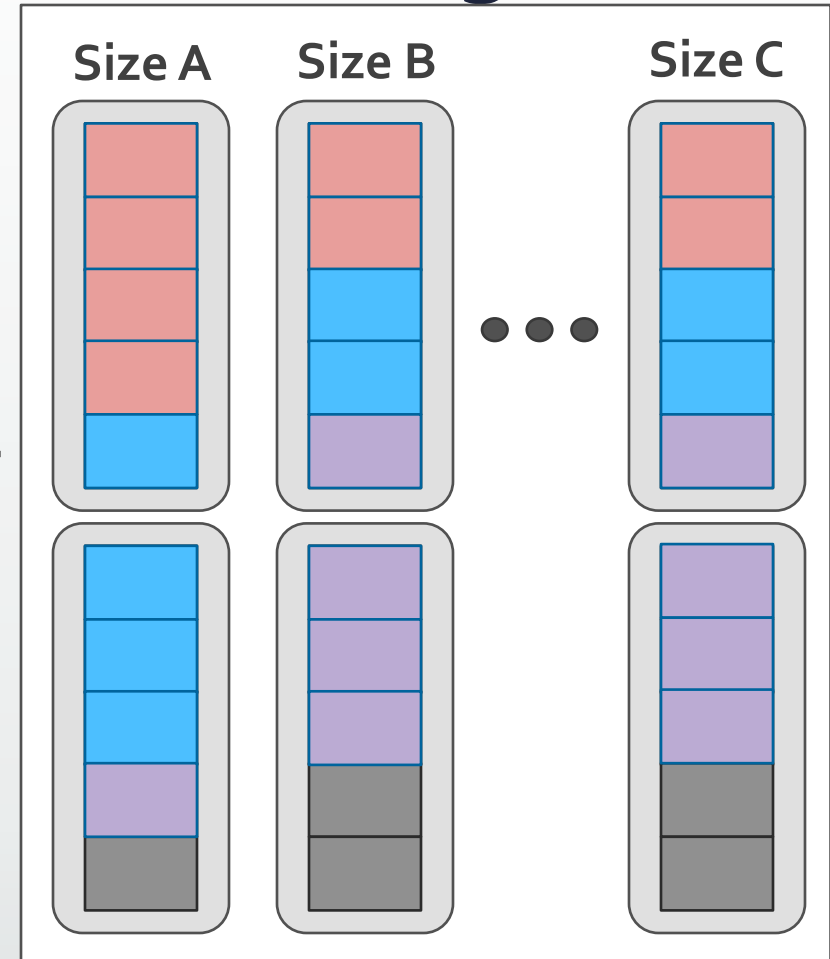
$\{ (r_1, a_1), (r_2, a_2), (r_3, a_3) \}$



$\{ (r_1, c_1), (r_2, c_2), (r_3, c_3) \}$



$\{ (r_1, b_1), (r_2, b_2), (r_3, b_3) \}$



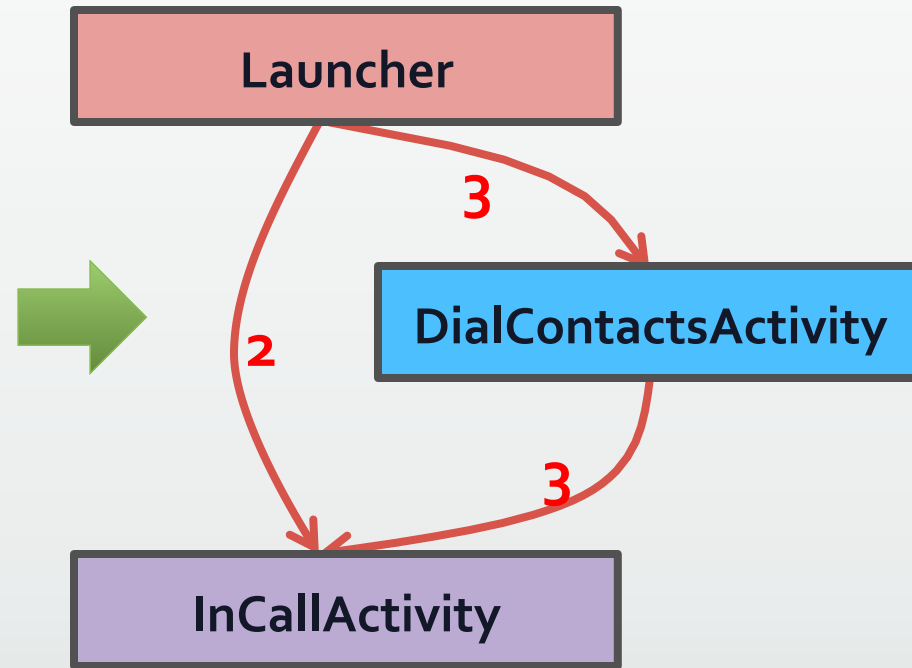
Memory Allocator

Temporal Ordering From Spatial Ordering

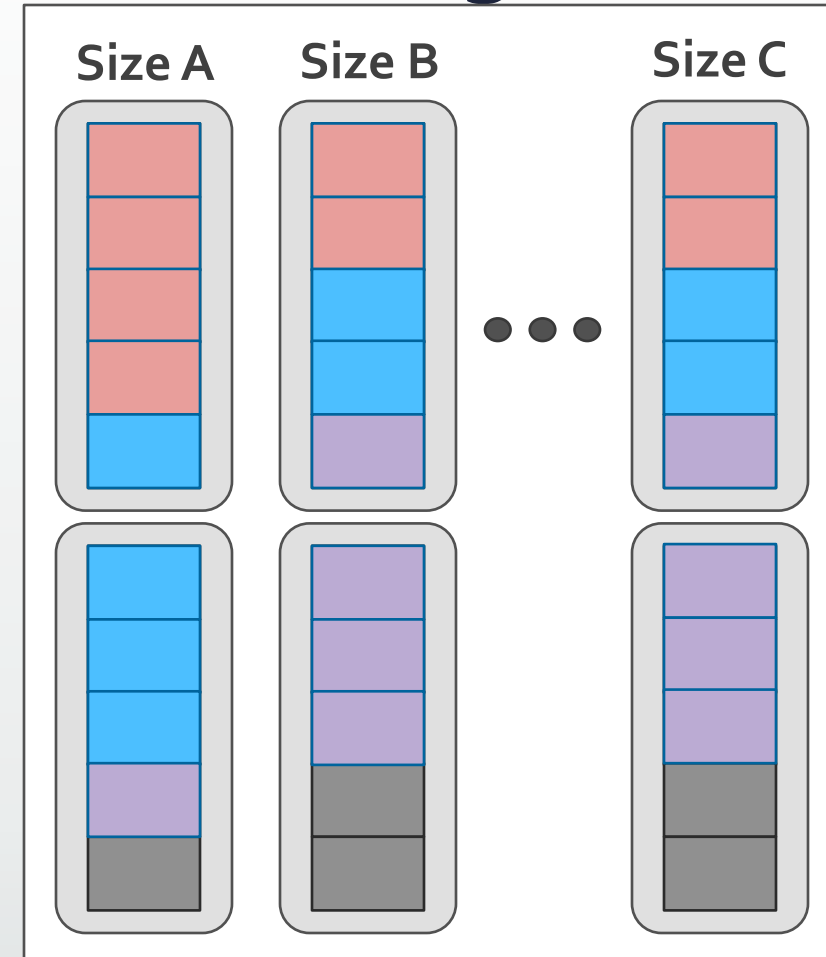
$\text{allPrecede}(e,f) = \{ r \mid (r,m) \in e \wedge (r,n) \in f \wedge \max(m) < \min(n) \}$ |
 $\text{anySucceed}(e,f) = \{ r \mid (r,m) \in e \wedge (r,n) \in f \wedge \max(m) > \min(n) \}$ |

```

Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B E2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
    
```



Transition Graph

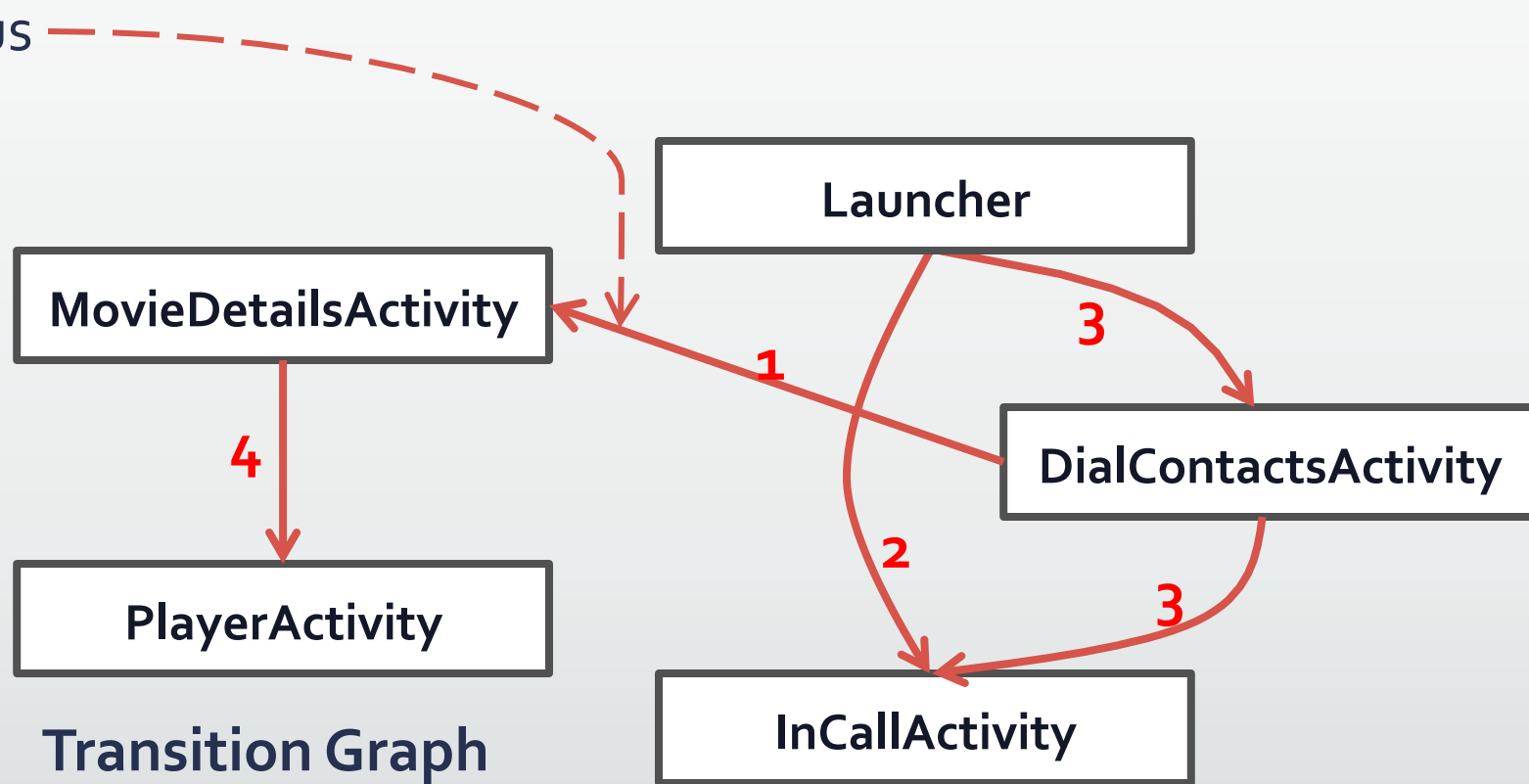


Memory Allocator

Pruning Erroneous Edges

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8B 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

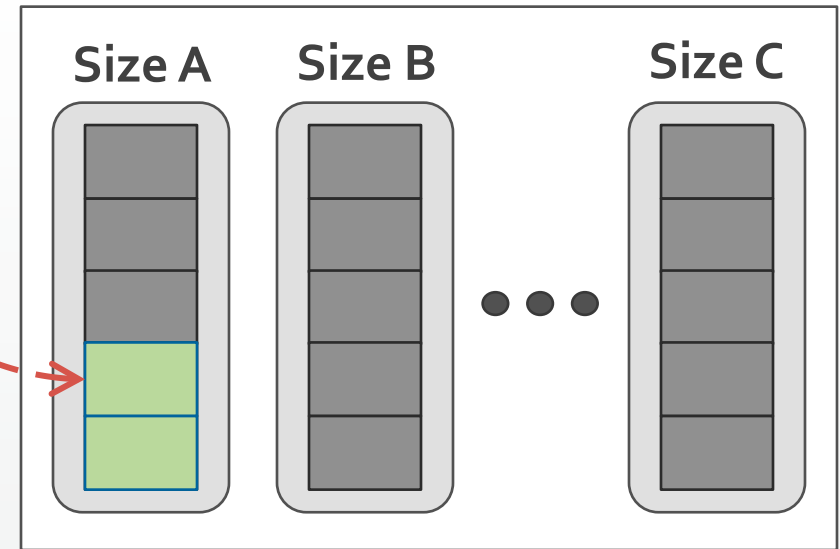
Erroneous
Edge



Transition Graph

Pruning Erroneous Edges

Existing Allocation



Launcher

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 FO 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8B 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



MovieDetailsActivity

4

PlayerActivity

Transition Graph

Pruning Erroneous Edges

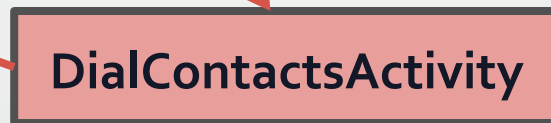
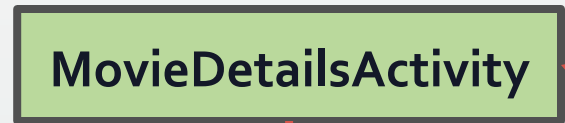
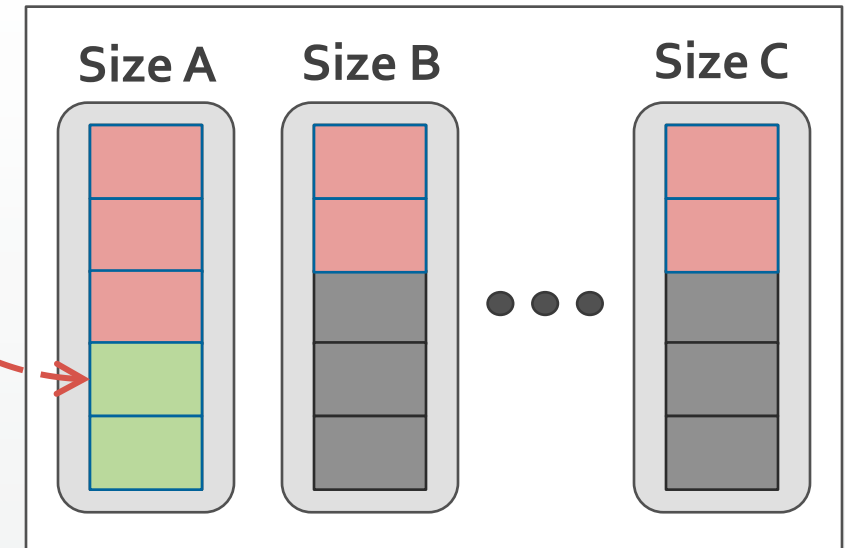
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Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 FO 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
    
```

Erroneous Edge



Existing Allocation



Transition Graph

4

1

3

DialContactsActivity

PlayerActivity

MovieDetailsActivity

Launcher

Size A

Size B

Size C

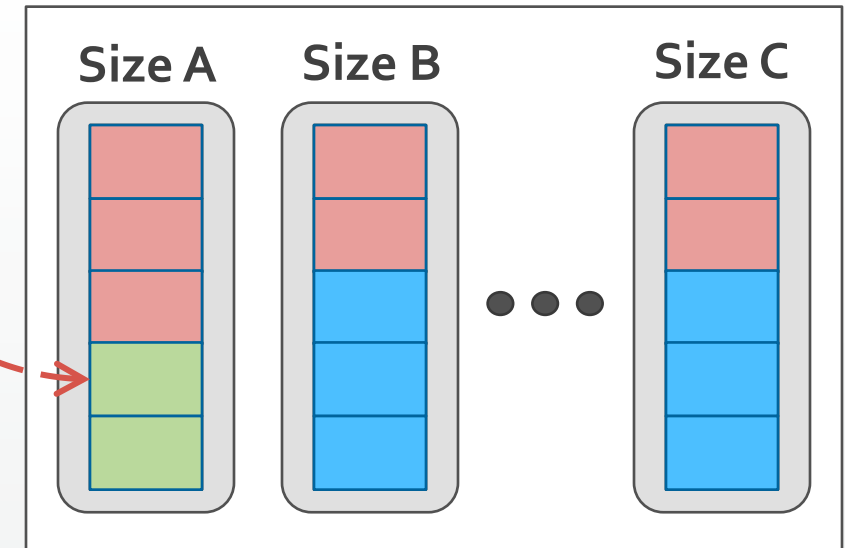
Pruning Erroneous Edges

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 FO 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

Erroneous Edge



Existing Allocation



Transition Graph

4

1

2

3

3

Pruning Erroneous Edges

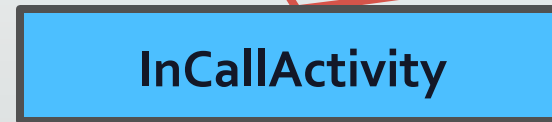
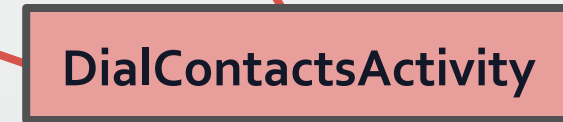
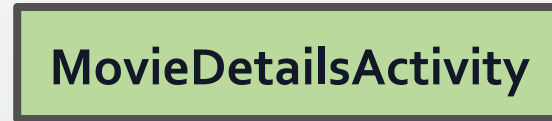
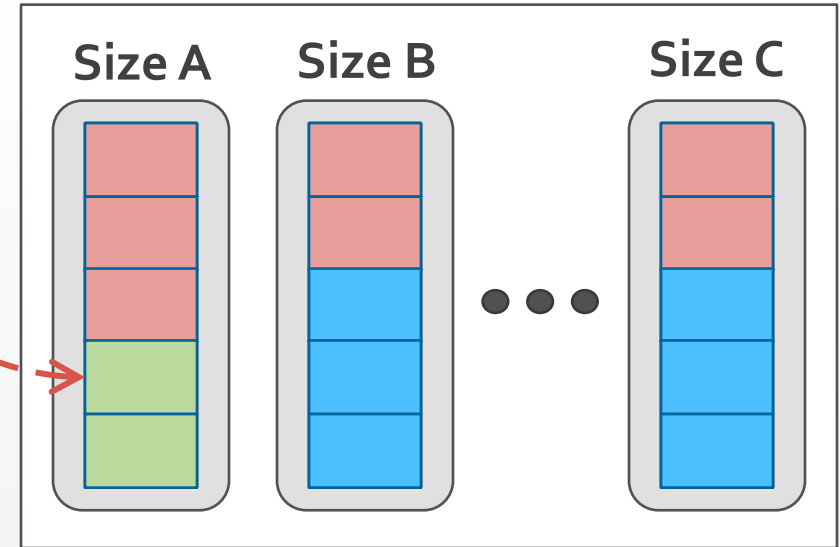
```

Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 FO 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
    
```

Erroneous Edge



Existing Allocation



Min-Cut

Undirected Transition Graph

4

1

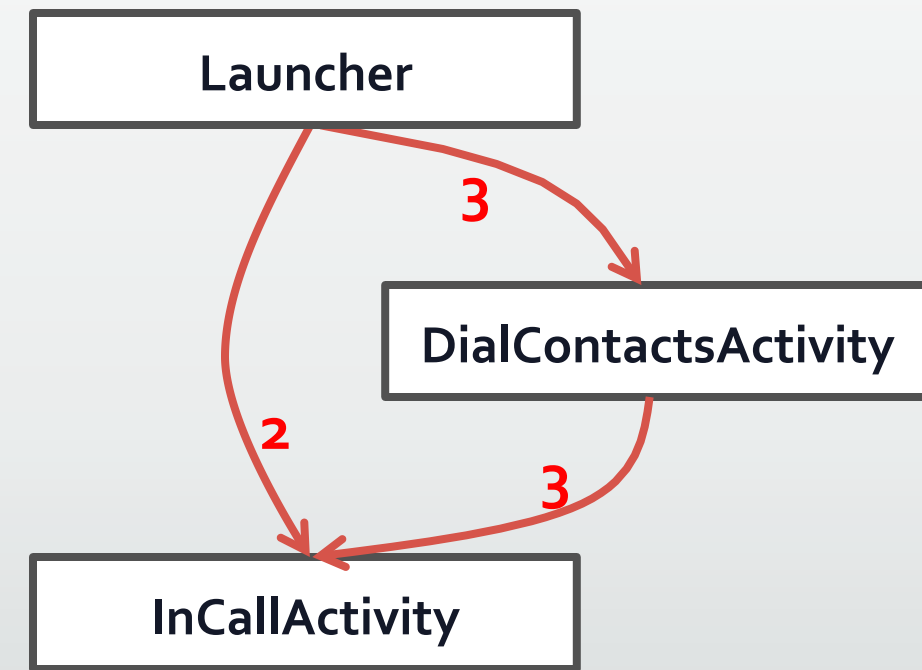
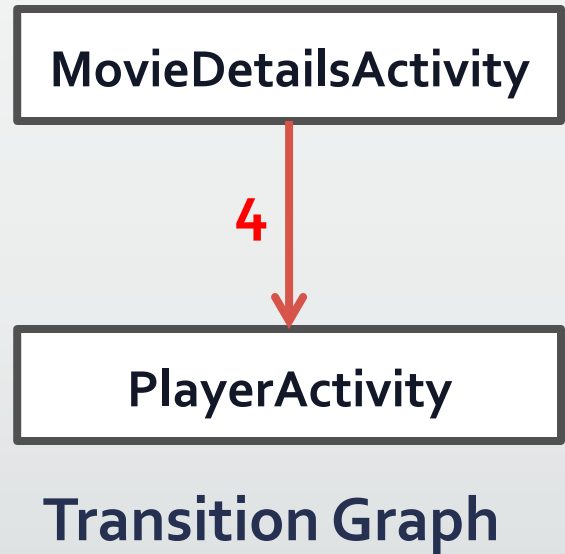
3

2

3

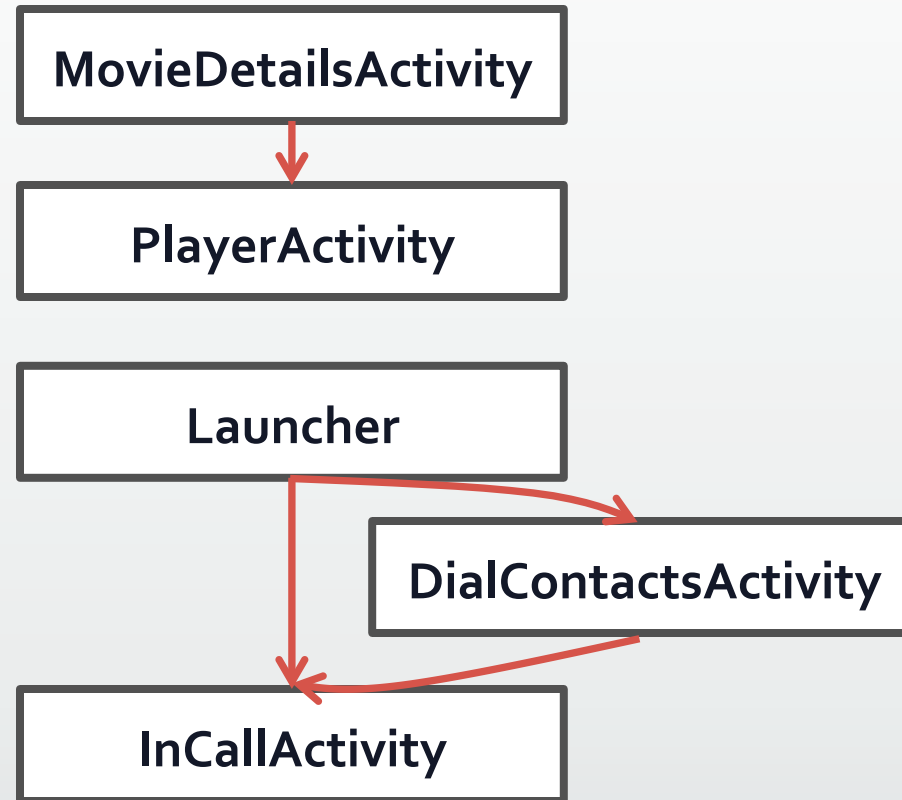
Pruning Erroneous Edges

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



Global Ordering

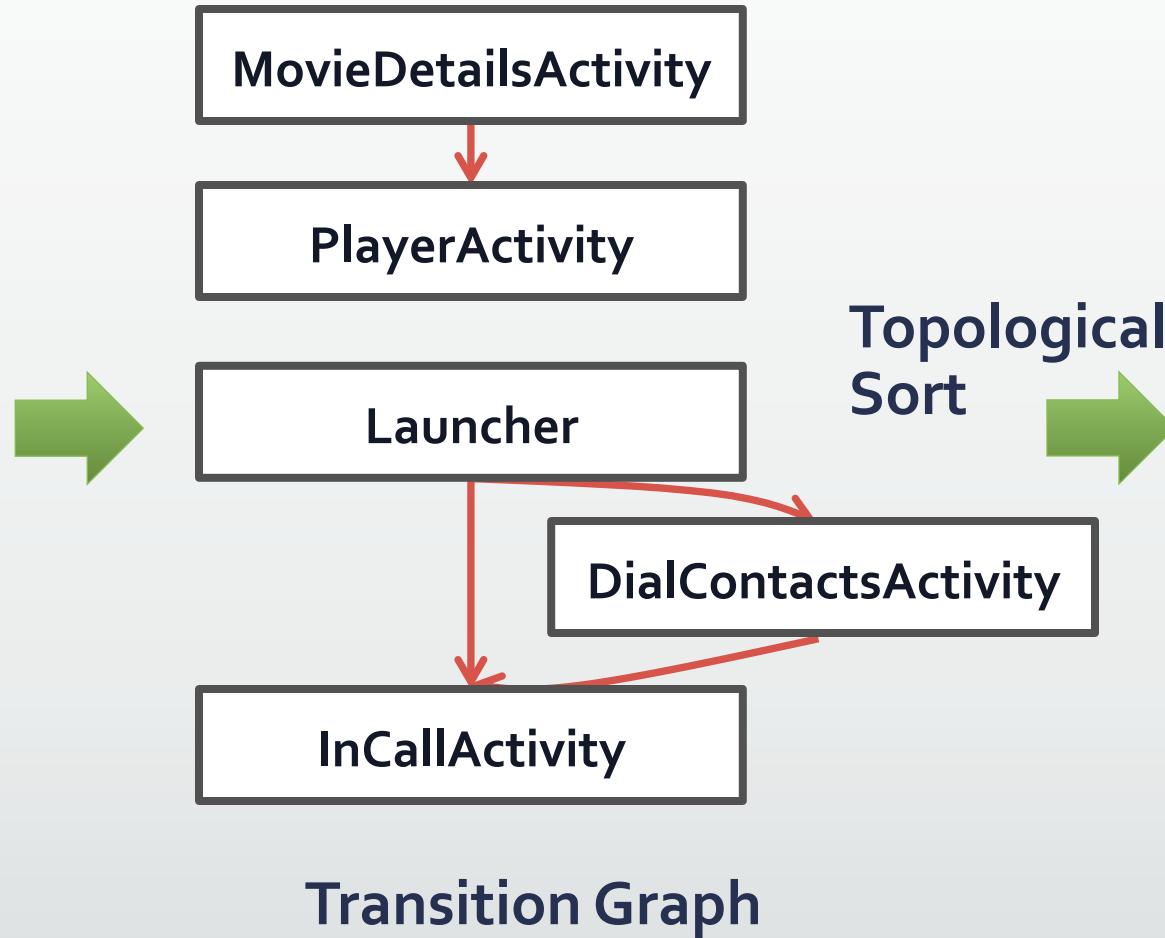
```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B E2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



Transition Graph

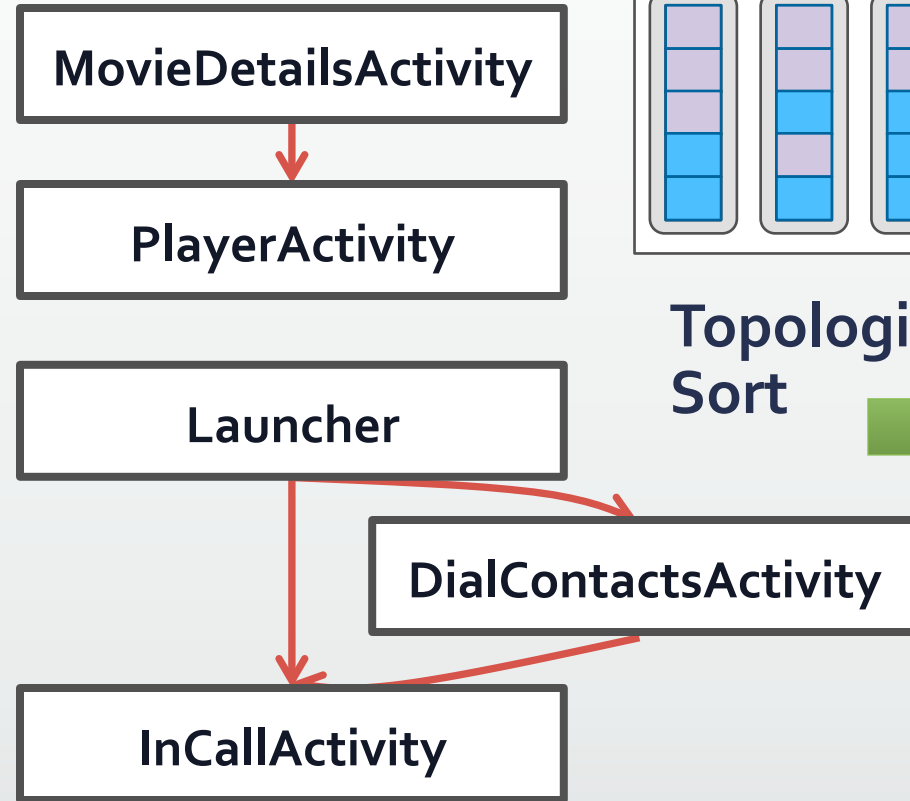
Global Ordering

```
Memory dump
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3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

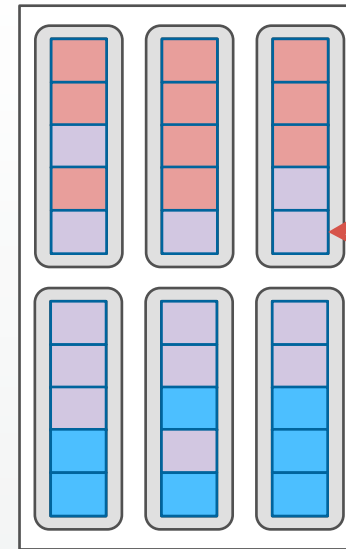


Global Ordering

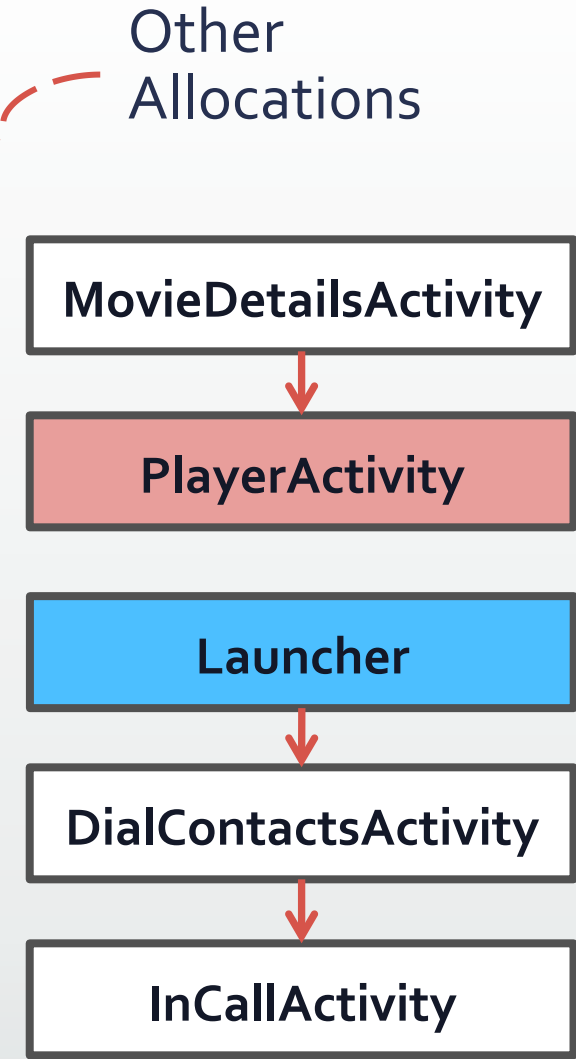
```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
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30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 BA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



Transition Graph



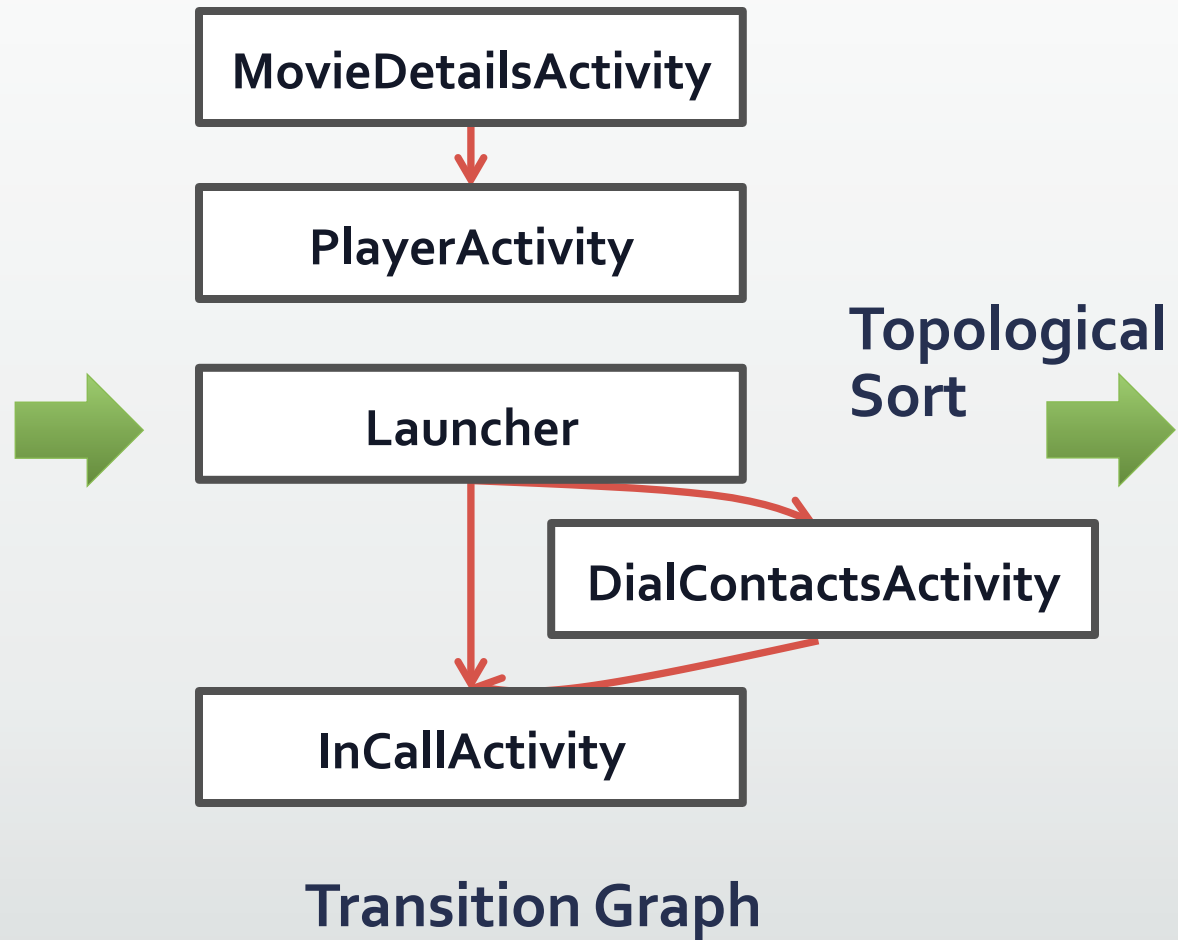
Topological Sort



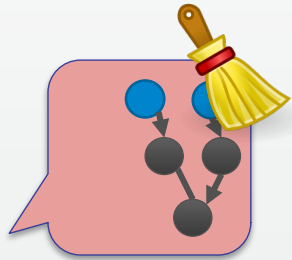
Local Orderings

Global Ordering

```
Memory dump
2FF0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3000 AF 21 F4 31 CD 1F 31 21 EB 31 CD 1F 31 CD 89 46
3010 21 00 50 11 F0 03 CD 8F 46 21 00 58 11 FF 07 36
3020 70 23 1B 7B B2 20 F8 CD 98 46 CD B9 46 CD 3E 00
3030 CD 1B 00 FE 53 CA 3F 30 FE 31 CA 00 00 18 F1 06
3040 BE AF 21 2C 31 77 23 10 FC 3E 18 32 FE 31 21 50
3050 D0 11 98 03 CD 8F 46 AF 32 26 31 32 4F 31 21 EB
3060 31 CD 1F 31 32 F7 31 32 F8 31 3E 03 32 25 31 21
3070 CB 52 22 27 31 3E 08 32 F9 31 CD 8D 47 0E 16 AF
3080 32 DE 31 CD 52 41 CD 95 33 3E 01 32 2B 31 3E 08
3090 32 D9 31 AF 32 DB 48 32 DC 48 32 DF 48 32 DE 48
30A0 32 DD 48 21 00 00 22 4A 31 22 4D 31 21 00 01 22
30B0 54 31 11 56 31 CD A8 35 11 6F 31 CD A8 35 11 88
30C0 31 CD A8 35 11 A1 31 CD A8 35 11 BA 31 CD A8 35
30D0 11 00 00 AF CD 33 00 CD 3E 00 21 56 31 11 17 00
30E0 19 36 20 11 19 00 19 36 30 19 36 50 19 36 60 19
30F0 36 20 CD BF 48 C3 01 32 06 13 21 63 D0 11 27 00
3100 3E 76 77 19 10 FC 06 13 21 64 D0 11 29 00 3E 77
3110 77 19 10 FC 06 28 0E 3C 21 28 D0 CD 56 3D C9 77
3120 23 77 23 77 C9 03 00 EA D2 00 00 01 00 01 01 03
3130 00 8B 50 02 0D 00 1F 3C 0A 04 3E 00 00 20 3C 31
3140 3C 8E 53 20 00 00 00 17 54 00 0E 00 01 00 00 03
3150 FF D0 00 00 00 01 00 00 00 00 00 00 00 00 00 00
3160 00 00 00 00 00 00 00 00 00 00 00 00 00 20 00 00
3170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```



Garbage Collection



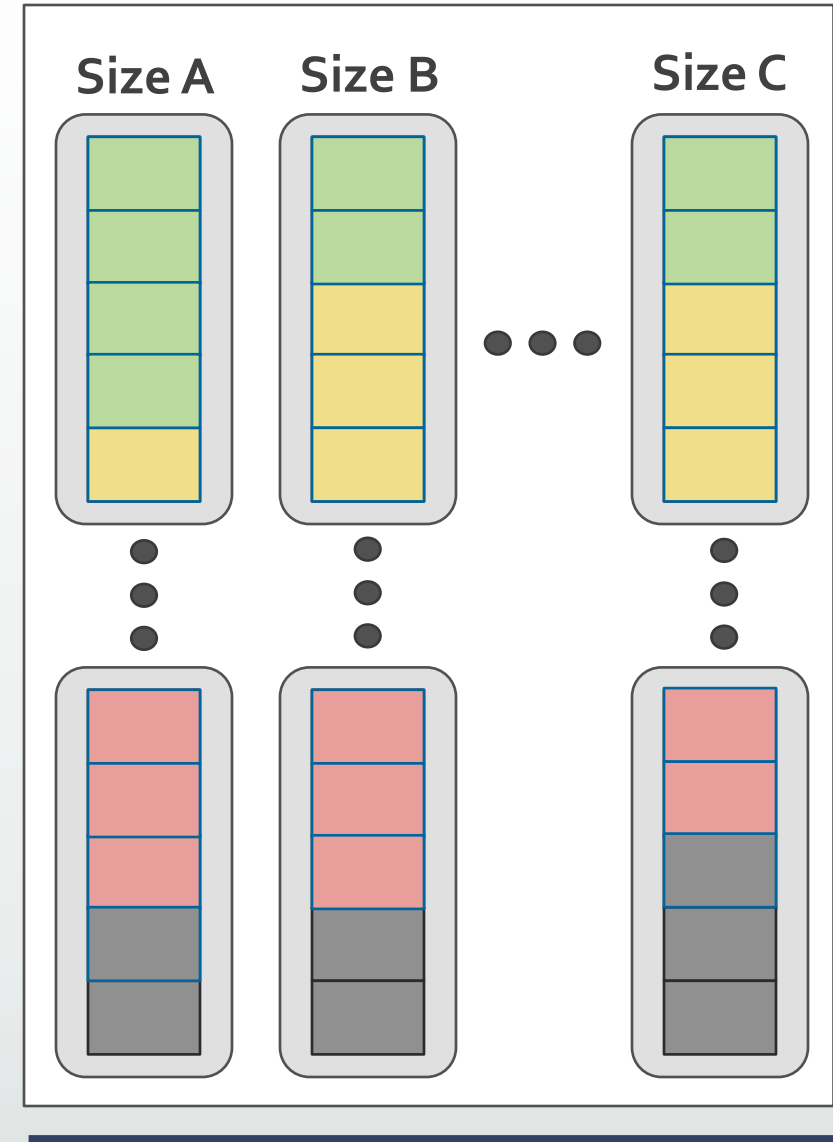
Garbage Collected
Activity

Garbage Collection frees up
prior runs, potentially causing a
spatial disordering

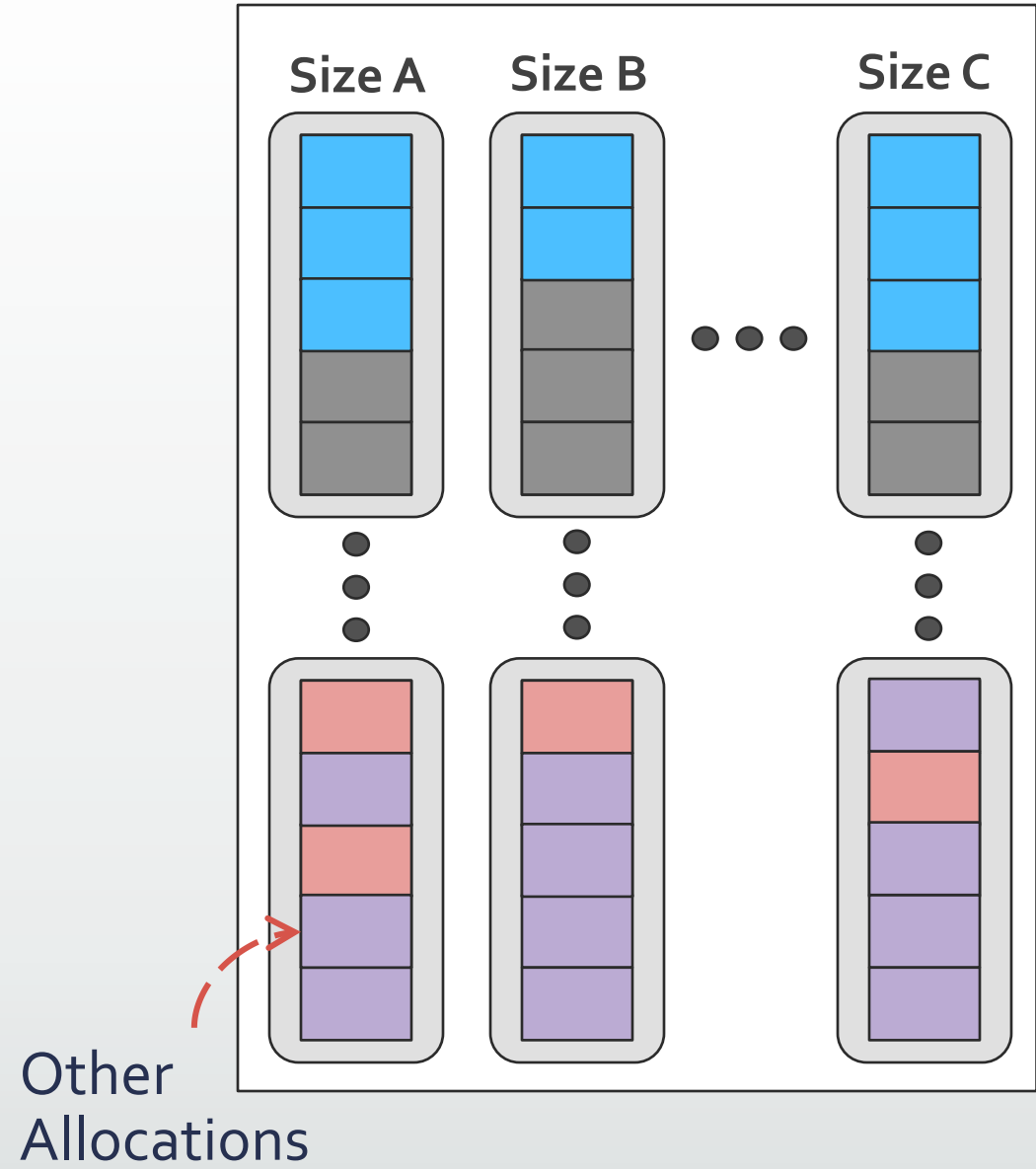
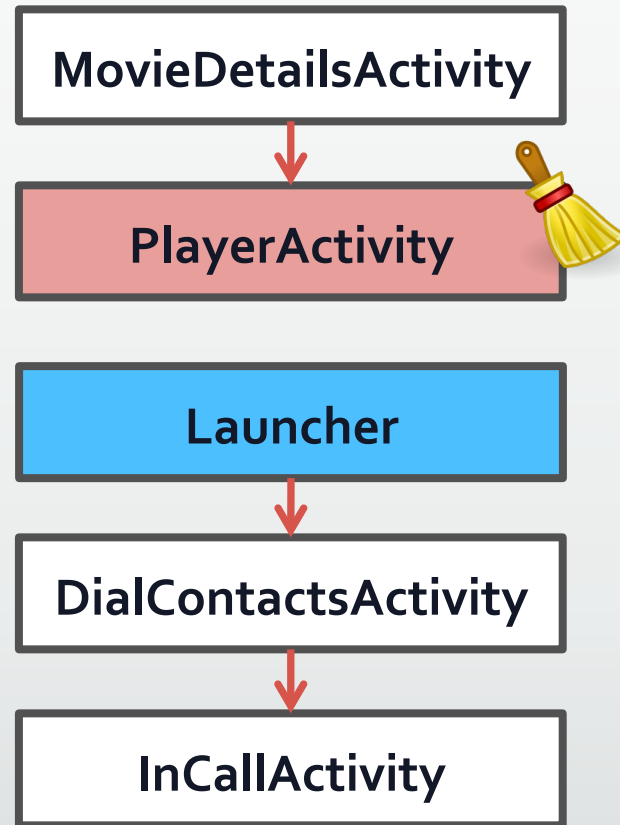
Conver~~s~~ation

Conver~~s~~ionList

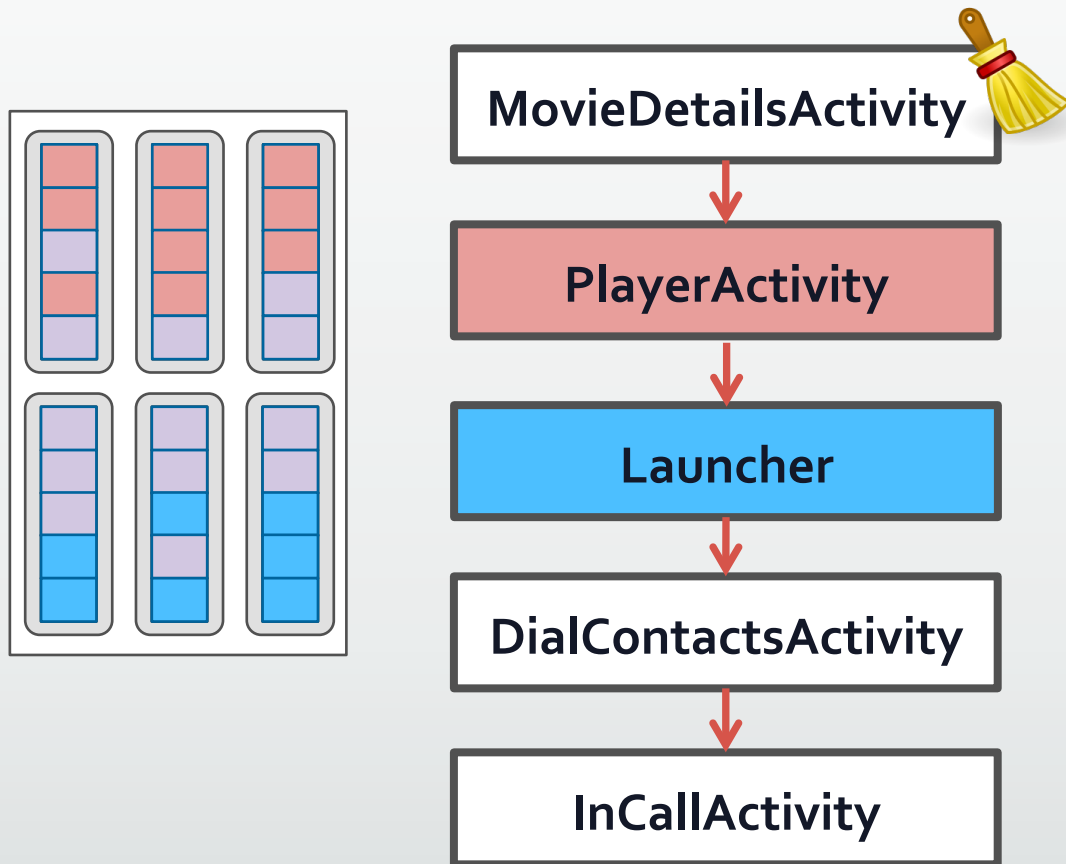
PlayerActivity



Garbage Collection



Garbage Collection



Joinable Local Orderings do not end in Garbage Collected Activities

Period of Garbage Collection
Active Usage: 41-50 minutes
Idle: 98-112 minutes

Micro-Benchmarks

Test Sequence	# of Activity Ordered	# Of Paths	Ground Truth Distance
A	16	1	0
B			
C			
D	12	1	0
E	14	1	0
F	15	1	0

Recovered Activity Launched Before Test Sequence

Samsung S4 (Android 5.0)

Test Sequence	# of Activity Ordered	# Of Paths	Ground Truth Distance
A			0
B			0
G	15	1	0
	16	1	0
	14	1	0
J	16	1	0

10 Test Sequences A-J

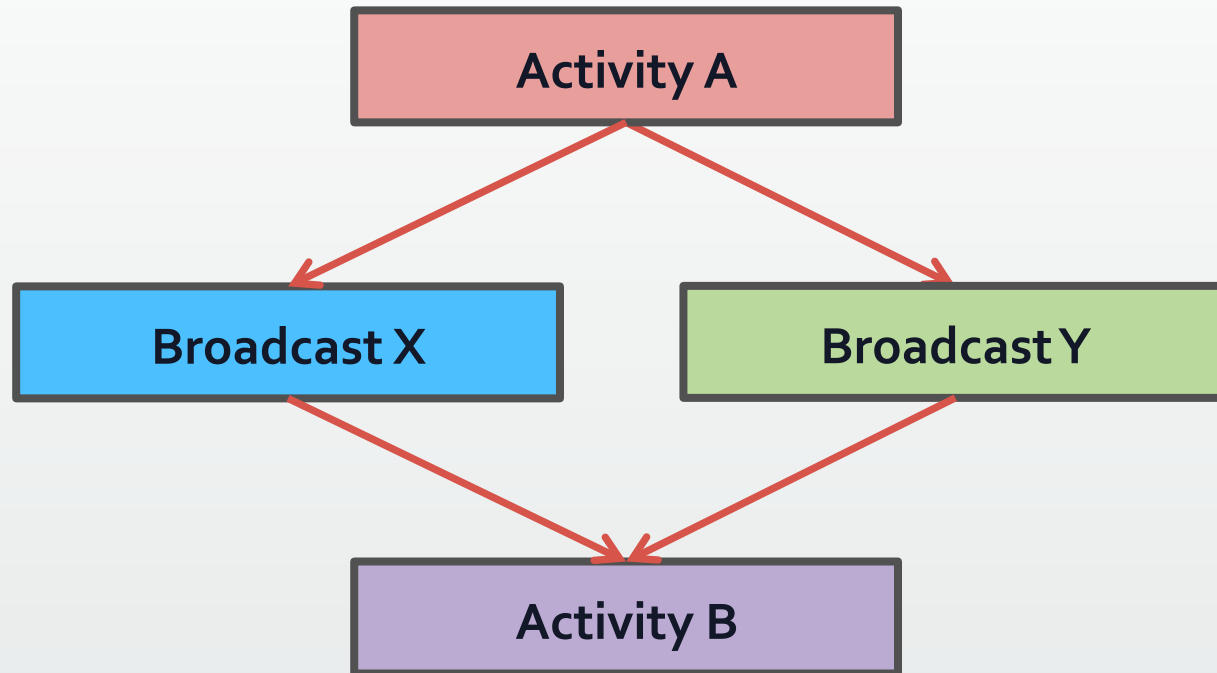
Accurate Results

LG G3 (Android 5.1)

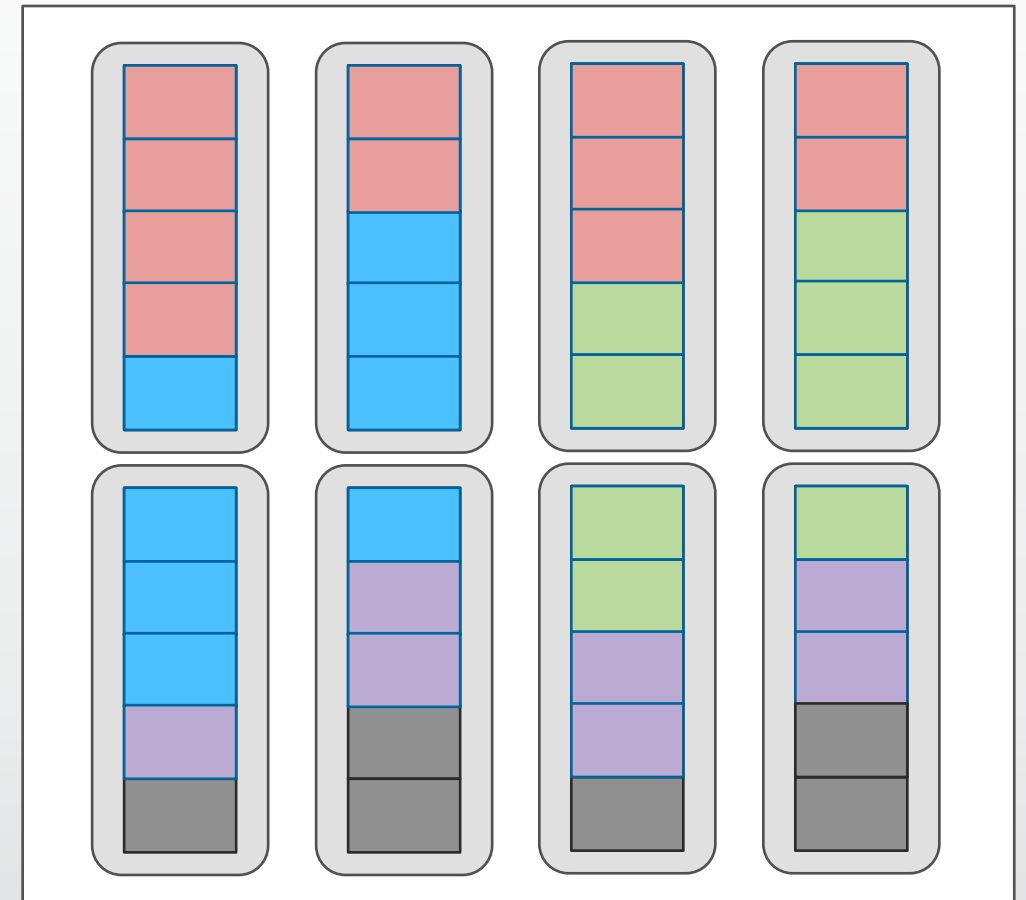
Test Sequence	# of Activity Ordered	# Of Paths	Ground Truth Distance
A	15	1	0
C	15	1	0
D	12	1	0
G	14	1	0
H	14	1	0
I	14	1	0

Moto G3 (Android 6.0)

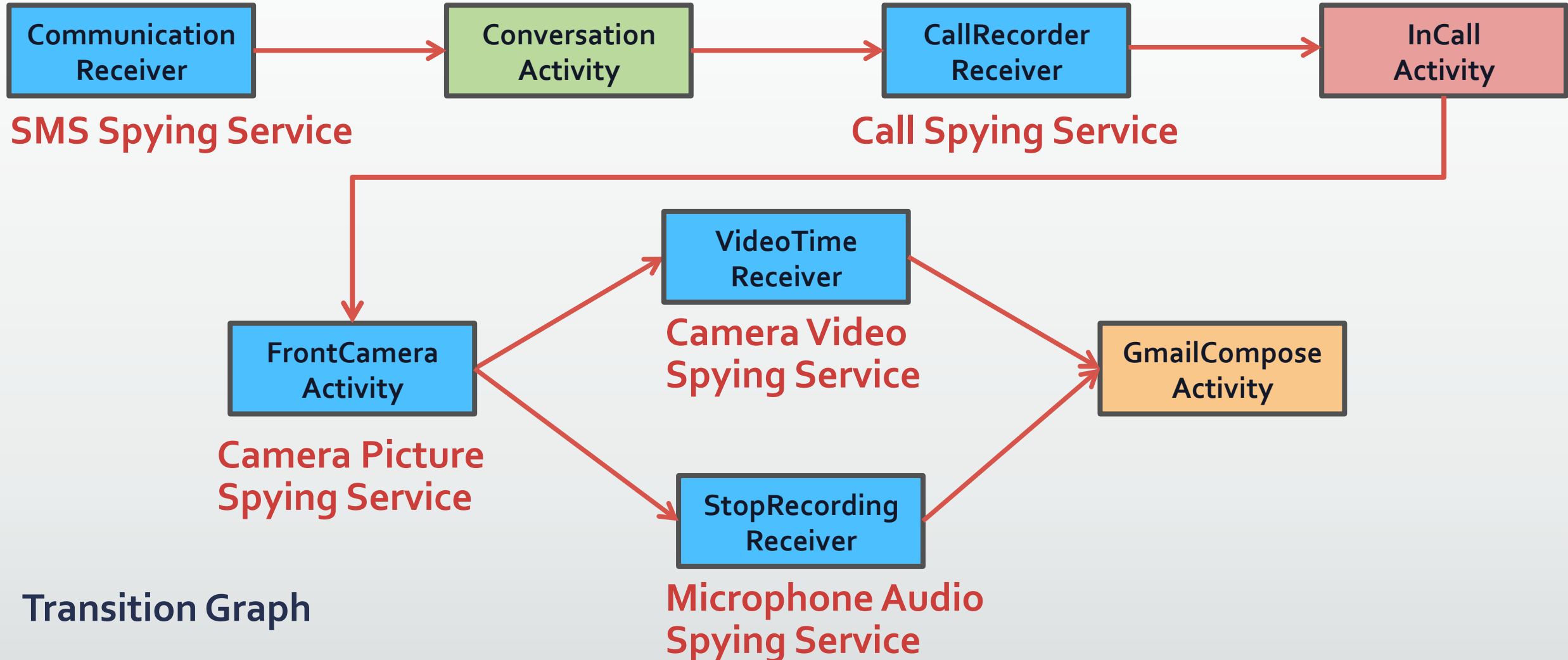
Design Generality: Spyware Attack Investigation



Transition Graph



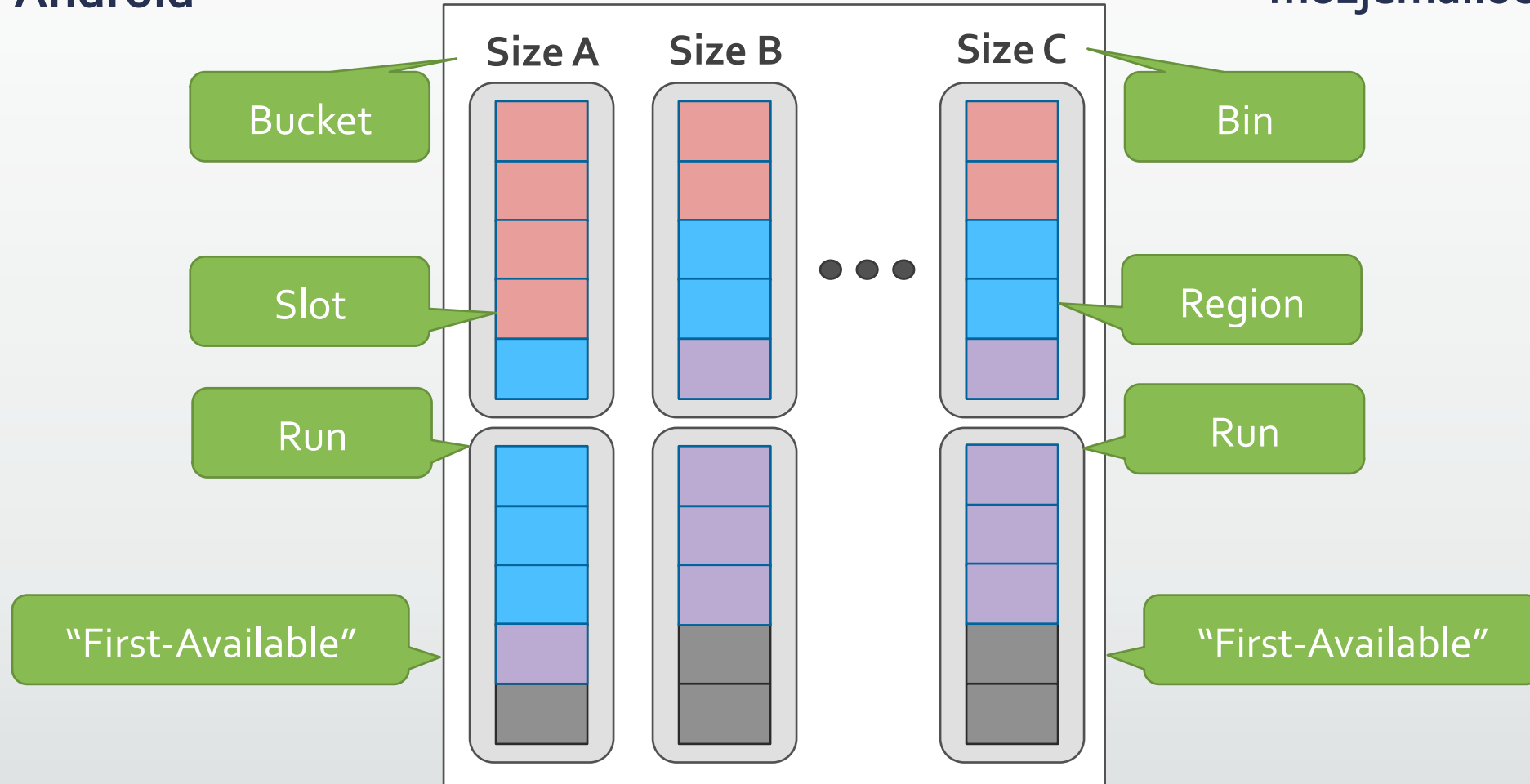
Design Generality: Spyware Attack Investigation



Design Generality: Extension to jemalloc

Android

mozjemalloc



Case Study

**Initially, the driver is using the
Google Maps Navigation app**

Conclusion

Timeliner re-sequences an Android user's past actions, even for terminated applications

Timeliner infers temporal ordering of Activities from memory layout of key self-identifying data structures

Accurate reconstruction of various applicable crime scenarios and extension beyond user actions and Android

Thank You!

Questions?

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