Approximate Judgement Aggregation
(for the case of the doctrinal paradox)

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Agenda

- Doctrinal Paradox
- Research Question : Approximate Aggregation
- Approximate Aggregation Results
  - for The Doctrinal Paradox
  - for Other Agendas
  - for a Class of Agendas
- Conclusion

Doctrinal Paradox (Unpacking the court/ Kornhauser and Sager 1986)

Suppose a defendant is accused in court of murder. In order to prove his guiltiness, one should convince the judge of two independent issues:

(A) The defendant killed the victim

(B) The defendant is sane

Conviction is defined to be the conjunction of the first two issues

$(A \wedge B)$ The defendant is guilty.

Doctrinal Paradox (Unpacking the court/ Kornhauser and Sager 1986)

A (Killed)	B (Sane)	$A \wedge B$ (Guilty)
0	1	0
1	0	0
1	1	1
0	0	0

Doctrinal Paradox (Unpacking the court/ Kornhauser and Sager 1986)

	A (Killed)	B (Sane)	$A \wedge B$ (Guilty)	
Agenda	0	1	0	
	1	0	0	
	1	1	1	
	0	0	0	
	0	1	1	$\leftarrow$ *inconsistent*
	1	0	1	$\leftarrow$ *inconsistent*
	1	1	0	$\leftarrow$ *inconsistent*
	0	0	1	$\leftarrow$ *inconsistent*

Doctrinal Paradox (Unpacking the court/ Kornhauser and Sager 1986)

	A (Killed)	B (Sane)	$A \wedge B$ (Guilty)
Judge 1	1	0	0
Judge 2	1	1	1
Judge 3	0	1	0
Majority	1	1	0

Notations

A profile $X \in \{0,1\}^{n \times m}$ $\left(\begin{array}{rl} n & \text{: Number of voters} \\ m = 3 & \text{: Number of issues} \end{array} \right)$

$$\begin{array}{ccc} X_1^1 & X_1^2 & X_i^3 \\ \vdots & \vdots & \vdots \\ X_i^1 & X_i^2 & X_i^3 \\ \vdots & \vdots & \vdots \\ X_n^1 & X_n^2 & X_n^3 \end{array}$$

The opinion of the i th voter on the 2 nd issue

Notations

$$\begin{array}{lll} X_1^1 & X_1^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \end{array}$$

The i$^{\text{th}}$ row X_i represents the **consistent** opinion of the i$^{\text{th}}$ voter

Notations

$$\begin{array}{ccc} X_1^1 & X_1^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \end{array}$$

The j<u>th</u> column X^j represents the opinions of all voters on the j<u>th</u> issue

Notations

$$F\begin{pmatrix} X_1^1 & X_1^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \end{pmatrix} = (\mathbf{a_1}, \mathbf{a_2}, \mathbf{a_3})$$

An **aggregation mechanism** returns for every profile an **aggregated opinion**

$$F : \{\{0,1\}^m\}^n \to \{0,1\}^m$$

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Definition (Consistency)

F is **consistent** if it returns a consistent result whenever all voters voted consistently

$$a_3 = a_1 \wedge a_2$$

Notations

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Definition (Independence)

F is **independent** if the aggregated opinion of the j$^{\text{th}}$ issue depends solely on the votes for the j$^{\text{th}}$ issue

Notations

$$F\begin{pmatrix} \mathbf{X_1^1} & X_1^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ \mathbf{X_i^1} & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ \mathbf{X_n^1} & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \end{pmatrix} = (\mathbf{a_1}, \mathbf{a_2}, \mathbf{a_3})$$

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F is **independent** if the aggregated opinion of the j^th issue depends solely on the votes for the j^th issue

Aggregation Mechanism - Examples

$$
\begin{array}{ccc}
X_1^1 & X_1^2 & X_1^3 = X_1^1 \wedge X_1^2 \\
\vdots & \vdots & \vdots \\
X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\
\vdots & \vdots & \vdots \\
X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2
\end{array}
$$

Aggregation Mechanism - Examples

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\vdots & \vdots & \vdots \\
X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \\
\hline
\end{array}
$$

Issue-wise Majority : $Maj(X^1)$ $Maj(X^2)$ $Maj(X^3)$

Independence: ✓

Consistency: X

Aggregation Mechanism - Examples

$$
\begin{array}{lccc}
 & X_1^1 & X_1^2 & X_1^3 = X_1^1 \wedge X_1^2 \\
 & \vdots & \vdots & \vdots \\
 & X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\
 & \vdots & \vdots & \vdots \\
 & X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \\
\hline
\text{Premise Majority}: & Maj(X^1) & Maj(X^2) & Maj(X^1) \wedge Maj(X^2)
\end{array}
$$

Independence: ✗
Consistency: ✓

Aggregation Mechanism - Examples

	X_1^1	X_1^2	$X_1^3 = X_1^1 \wedge X_1^2$
	$\vdots$	$\vdots$	$\vdots$
	X_i^1	X_i^2	$X_i^3 = X_i^1 \wedge X_i^2$
	$\vdots$	$\vdots$	$\vdots$
	X_n^1	X_n^2	$X_n^3 = X_n^1 \wedge X_n^2$
Constant:	0	$g(X^2)$	0

Independence: ✓
Consistency: ✓

Aggregation Mechanism - Examples

	X_1^1	X_1^2	$X_1^3 = X_1^1 \wedge X_1^2$
	$\vdots$	$\vdots$	$\vdots$
	X_i^1	X_i^2	$X_i^3 = X_i^1 \wedge X_i^2$
	$\vdots$	$\vdots$	$\vdots$
	X_n^1	X_n^2	$X_n^3 = X_n^1 \wedge X_n^2$
Oligarchy:	$\bigwedge X^1$	$\bigwedge X^2$	$\bigwedge X^3$

Independence: ✓
Consistency: ✓

Aggregation Mechanism - Examples

$$\begin{array}{ccc} X_1^1 & X_1^2 & X_1^3 = X_1^1 \wedge X_1^2 \\ \vdots & \vdots & \vdots \\ X_i^1 & X_i^2 & X_i^3 = X_i^1 \wedge X_i^2 \\ \vdots & \vdots & \vdots \\ X_n^1 & X_n^2 & X_n^3 = X_n^1 \wedge X_n^2 \\ \hline \end{array}$$

Independence:
Consistency:

Are there any other consistent and independent aggregation mechanisms?

$\langle A, B, A \wedge B \rangle$ - Oligarchy

Definition (Oligarchy)

An oligarchy of S returns 1
iff all the members of S voted 1.

$$u_S(\bar{x}) = \bigwedge_{i \in S} x_i$$

Theorem

Let F be an independent and consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
Then there exists three boolean functions
$f, g, h : \{0,1\}^n \rightarrow \{0,1\}$ *s.t.* $F(X) = \langle f(X^1), g(X^2), h(X^3) \rangle$
and $f = h \equiv 0$
or $g = h \equiv 0$
or $f = g = h$ *and it is an oligarchy.*

This theorem is a direct corollary from a series of works in the more general framework of aggregation.
(E.g., Nehring&Puppe 2007, Holzman&Dokow 2008)

Research Question

Theorem

Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.

Then

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Then

Definition (δ-consistent)

F is δ-consistent if the following test fails with probability at most δ:

Choose a consistent profile X uniformly at random.
Check whether $F(X)$ is a consistent opinion.

Research Question

Theorem

Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
Then

Definition (δ-independent)

F is δ-independent if the following test fails with probability at most δ:

Choose a consistent profile X uniformly at random.
Choose an issue j uniformly at random .
Choose a random consistent profile Y s.t. $X^j = Y^j$.
Check whether $(F(X))^j$ equals $(F(Y))^j$

Research Question

Theorem

Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
Then

Notice that

$$0\text{-consistency} \equiv \text{Consistency}$$
$$0\text{-independence} \equiv \text{Independence}$$

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Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
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Notice that

$$0\text{-consistency} \equiv \text{Consistency}$$
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Moreover, for $\delta < C \cdot 4^{-n} \approx \frac{1}{\text{Number of profiles}}$

$$\delta\text{-consistency} \equiv \text{Consistency}$$
$$\delta\text{-independence} \equiv \text{Independence}$$

Research Question

Theorem

Let $\delta > exp(n, \epsilon)$
Let F *be a* δ*-independent and* δ*-consistent aggregation mechanism for* $\langle A, B, A \wedge B \rangle$ *.*
Then there exists an independent and consistent aggregation mechanism G *that agrees with* F *on at least* $1 - \epsilon$ *of the profiles.*

Notice that

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Research Question

Theorem

Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
Then there exists an independent and consistent aggregation mechanism G that agrees with F on at least $1 - \epsilon$ of the profiles.

The other direction is trivial

Theorem

Let F and G be two aggregation mechanisms for $\langle A, B, A \wedge B \rangle$ such that

- *G is independent and consistent*
- *F and G agree on at least $1 - \epsilon$ of the profiles*

then F is ϵ-independent and 6ϵ-consistent.

Main result for $\langle A, B, A \wedge B \rangle$

Theorem

For any $\epsilon > 0$ and $\delta = poly(\epsilon, n)$: $(\delta \approx C \cdot n^{-2} \epsilon^5)$
Let F be a δ-independent and δ-consistent aggregation mechanism for $\langle A, B, A \wedge B \rangle$.
Then there exists an independent and consistent aggregation mechanism G that agrees with F on at least $1 - \epsilon$ of the profiles.

Techniques - How did we get this result?

- Restricting ourself to independent mechanisms.
- Applying an (agenda independent) technique to extend the result to δ-independence and δ-consistency.

Techniques - How did we get this result?

Given an independent δ-consistent aggregation mechanism $F = \langle f, g, h \rangle$

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Definition (Influence (Banzhaf Power Index))

The **influence** of the i$^{\text{th}}$ voter on f is the probability he can change the result by changing his vote.

$$I_i(f) = \Pr[f(x) \neq f(x \oplus e_i)]$$

Definition (Ignorability)

The **ignorability** of the i$^{\text{th}}$ voter on f is the probability f returns 1 although i voted 0.

$$P_i(f) = \Pr[f(x) = 1 | x_i = 0]$$

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Techniques - How did we get this result?

Given an independent δ-consistent aggregation mechanism $F = \langle f, g, h \rangle$
We show that

- f is an oligarchy iff

$$\forall i \ : \ I_i(f)P_i(f) = 0$$

Techniques - How did we get this result?

Given an independent δ-consistent aggregation mechanism $F = \langle f, g, h \rangle$
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-

$$\forall i \; : \; I_i(f)P_i(g) \leqslant 4\delta$$

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We show that

- f is an oligarchy iff

$$\forall i \ : \ I_i(f)P_i(f) = 0$$

- $$\forall i \ : \ I_i(f)P_i(g) \leqslant 4\delta$$

- Let u be the oligarchy of the voters with small ignorability (either $P_i(f)$ or $P_i(g)$) Then,

  f and g are close to u
  F is close to $\langle u, u, u \rangle$.

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- Doctrinal Paradox
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- Conclusion

Agenda

- Doctrinal Paradox
- Research Question : Approximate Aggregation
- Approximate Aggregation Results
  - for The Doctrinal Paradox
  - for Other Agendas
    - Preference Agenda
    - XOR Agenda $\langle A, B, A \oplus B \rangle$
  - for a Class of Agendas
- Conclusion

Other Agendas - Preference Aggregation

$a > b$	$b > c$	$c > a$	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
0	0	0	$\leftarrow$ *inconsistent*
1	1	1	$\leftarrow$ *inconsistent*

Other Agendas - Preference Aggregation

	a > b	b > c	c > a
Voter 1 :	1	1	0
Voter 2 :	0	1	1
Voter 3 :	1	0	1
Majority :	1	1	1

Theorem (Condorcet Paradox)

Pair-wise majority might lead to inconsistent outcome.

Other Agendas - Preference Aggregation

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Theorem (Arrow's Theorem 1950)

So is any other non-dictatorial aggregation mechanism that satisfies independence and Pareto.

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So is any other non-dictatorial aggregation mechanism that satisfies independence and Pareto.

Theorem (Kalai 2002 , Mossel 2009)

For any $\epsilon > 0$:
Let F be an independent, $K\epsilon$-consistent (and balanced) preference aggregation mechanism.
Then there exists an independent and consistent aggregation mechanism G(i.e., dictatorship) that agrees with F on at least $1 - \epsilon$ of the profiles.

Other Agendas - $\langle A, B, A \oplus B \rangle$

A	B	$A \oplus B$	
0	1	1	
1	0	1	
1	1	0	
0	0	0	
0	1	0	$\leftarrow$ *inconsistent*
1	0	0	$\leftarrow$ *inconsistent*
1	1	1	$\leftarrow$ *inconsistent*
0	0	1	$\leftarrow$ *inconsistent*

Other Agendas - $\langle A, B, A \oplus B \rangle$

Theorem

For any $\epsilon > 0$ *and* $\delta = poly(\epsilon, n)$*:* $(\delta = C \cdot \epsilon)$
Let F *be a* δ*-independent and* δ*-consistent aggregation mechanism for* $\langle A, B, A \oplus B \rangle$ *.*
Then there exists an independent and consistent aggregation mechanism G *that agrees with* F *on at least* $1 - \epsilon$ *of the profiles.*

Techniques - How did we get this result?

- Restricting ourself to independent mechanisms.
- Applying an (agenda independent) technique to extend the result to δ-independence and δ-consistency.

Techniques - How did we get this result?

Given an independent δ-consistent aggregation mechanism $F = \langle f, g, h \rangle$
We describe f,g, and h using Fourier representation and prove that

$$1 - 2\delta = \sum_{\chi} \widehat{f}(\chi)\widehat{g}(\chi)\widehat{h}(\chi)$$

when

- The summation is over all functions χ s.t. $\langle \chi, \chi, \chi \rangle$ is consistent
- $\left|\widehat{f}(\chi)\right|$ equals $1 - 2d$ for d being the distance between f and χ.

in order to get that F is 'close to' $\langle \chi, \chi, \chi \rangle$.

Main result

Theorem

For any $\epsilon > 0$, $m, n \geqslant 1$, *and* $\delta = poly\left(\frac{1}{n}, \epsilon, m\right)$*:*
Let $\mathbb{X}$ *be a premise-conclusion agenda over* m *issues in which each issue is either a premise, or a conclusion of at most two premises.*
Let F *be a* δ*-independent and* δ*-consistent aggregation mechanism for* $\mathbb{X}$ *.*
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Let F be a δ-independent and δ-consistent aggregation mechanism for $\mathbb{X}$.
Then there exists an independent and consistent aggregation mechanism G that agrees with F on at least $1 - \epsilon$ of the profiles.

For instance:

$\langle A, B, A \oplus B \rangle$

$\langle A, B, A \wedge B, A \vee B \rangle$

$\langle A, B, C, A \wedge B \vee C \rangle$

$\langle A, B, C, A \wedge B, B \oplus C, A \wedge C \rangle$

~~$\langle A \wedge B, B \wedge C, C \wedge A \rangle$~~

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$\langle A, B, C, A \wedge B, B \oplus C, A \wedge C \rangle$

~~$\langle A \wedge B, B \wedge C, C \wedge A \rangle$~~

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Technique:
- $\wedge$ and $\oplus$ represent all boolean functions of two arguments.
- Induction over the number of issues.

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- We defined the question of approximate aggregation.
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- Open question:

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- Open question:
  - Find an agenda and an aggregation mechanism that is δ-independent and δ-consistent but is far from any independent consistent aggregation mechanism.

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- We proved approximate aggregation theorems for a class of premise conclusion agendas.
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  - Find an agenda and an aggregation mechanism that is δ-independent and δ-consistent but is far from any independent consistent aggregation mechanism.

Thank You

More information

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Paper: http://arxiv.org/abs/1008.3829

Please write me any comments/questions/suggestions you have.