Spans

December 3, 2023

00QB This chapter contains some material about spans. Notably, we discuss and explore:

1. The basic definitions around spans (Section 1);
2. The relation between spans and functions (Proposition 7.1.1.1);
3. The relation between spans and relations (Propositions 7.2.2.1 and 7.3.1.1 and Remark 7.5.1.1).
4. “Hyperpointed sets” (**??**). I don’t know why I wrote this...

TODO:

1. internal adjoint equivalences in **Rel**
2. internal adjoint equivalences in Span
3. 2-categorical limits in **Rel**;
4. morphism of internal adjunctions in **Rel**;
5. morphism of internal adjunctions in Span;
6. morphism of co/monads in Span;
7. What is $\mathrm{Adj}(\mathrm{Span}(A, B))$?
8. monoids, comonoids, pseudomonoids, etc. in Span.
9. write down the dumb intuition about spans inducing morphisms $\mathrm{Sets}(S, A) \to \mathrm{Sets}(S, B)$ instead of $\mathcal{P}(A) \to \mathcal{P}(B)$ from the similarity between
$$S \to A \times B$$
and
$$A \times B \to \{\mathrm{t}, \mathrm{f}\}.$$
This intuition is justified by taking $A = \mathrm{pt}$ or $B = \mathrm{pt}$.

10. What about using the direct image with compact support in $g\big(f^{-1}(a)\big)$?
11. Monads in Span | develop this in the level of morphisms too
12. Comonads in Span are spans whose legs are equal | develop this in the level of morphisms too
13. Does Span have an internal **Hom**?
14. Examples of spans
15. Functional and total spans
16. closed symmetric monoidal category of spans
17. double category of relations
18. collage of a span
19. equivalence spans?
20. functoriality of powersets for spans
21. Is Span a closed bicategory?
22. skew monoidal structure on Span(A, B)
23. Adjunctions in Span
24. Isomorphisms in Span
25. Equivalences in Span
26. Interaction between the above notions in Span vs.in **Rel** via the comparison functors

Contents

00QC 1 Spans

00QD 1.1 The Walking Span

00QE **Definition 1.1.1.1.** The **walking span** is the category Λ that looks like this:

$$\begin{tikzcd}
 & {[0]} \arrow[loop above] \arrow[dl] \arrow[dr] & \\
{[-1]} \arrow[loop left] & & {[1]} \arrow[loop right]
\end{tikzcd}$$

00QF 1.2 Spans

Let A and B be sets.

00QG **Definition 1.2.1.1.** A **span from A to B**[1] is a functor $F\colon \Lambda \longrightarrow \mathsf{Sets}$ such that

$$\begin{aligned}
F([-1]) &= A,\\
F([1]) &= B.
\end{aligned}$$

00QH **Remark 1.2.1.2.** In detail, a **span from A to B** is a triple (S, f, g) consisting of[2,3]

- *The Underlying Set.* A set S, called the **underlying set of** (S, f, g);
- *The Legs.* A pair of functions $f\colon S \longrightarrow A$ and $g\colon S \longrightarrow B$.

00QJ 1.3 Morphisms of Spans

00QK **Definition 1.3.1.1.** A **morphism of spans (R, f_1, g_1) to (S, f_2, g_2)**[4] is a natural transformation $(R, f_1, g_1) \Longrightarrow (S, f_2, g_2)$.

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[1] *Further Terminology:* Also called a **roof from A to B** or a **correspondence from A to B**.

[2] *Picture:*

$$\begin{tikzcd}
 & S \arrow[dl, "f"'] \arrow[dr, "g"] & \\
A & & B.
\end{tikzcd}$$

[3] Every span (S, f, g) from A to B determines in particular a relation $R\colon A \nrightarrow B$ via

$$R \overset{\text{def}}{=} \{(f(a), g(a)) \mid a \in A\},$$

i.e. where $R(a) = g\left(f^{-1}(a)\right)$ for each $a \in A$; see Proposition 7.2.2.1.

[4] *Further Terminology:* Also called a **morphism of roofs from (R, f_1, g_1) to (S, f_2, g_2)** or a **morphism of correspondences from (R, f_1, g_1) to (S, f_2, g_2)**.

00QL **Remark 1.3.1.2.** In detail, a **morphism of spans from** (R, f_1, g_1) **to** (S, f_2, g_2) is a function $\phi\colon R \longrightarrow S$ making the diagram[5]

$$\begin{tikzcd}
& R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] \arrow[rrr, "\phi"] & & & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] & \\
A \arrow[rrr, equal] & & B \arrow[rrr, equal] & A & & B.
\end{tikzcd}$$

commute.

00QM 1.4 Functional Spans

Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B\right)$ be a span. A morphism of spans from id_A to $\lambda \diamond \lambda^\dagger$ is a morphism

$$s\colon A \longrightarrow S \times_B S$$

making the diagram

$$\begin{tikzcd}
& A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] \arrow[dd, "s"] & \\
A & & A \\
& S \times_B S \arrow[ul, "f\circ\mathrm{pr}'_1"] \arrow[ur, "f\circ\mathrm{pr}'_2"'] &
\end{tikzcd}$$

commute, where $S \times_B S$ is the pullback

$$S \times_B S \cong \{(s,t) \in S \times S \mid g(s) = g(t)\} \qquad \begin{tikzcd}
S \times_B S \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & S \arrow[d, "g"] \\
S \arrow[r, "g"'] & B
\end{tikzcd}$$

of S with itself along g.

[5] *Alternative Picture:*

$$\begin{tikzcd}
& R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] \arrow[dd, "\phi"] & \\
A & & B. \\
& S \arrow[ul, "f_2"] \arrow[ur, "g_2"'] &
\end{tikzcd}$$

00QN **1.5 Total Spans**

00QP 2 Categories of Spans

00QQ 2.1 Categories of Spans

Let A and B be sets.

00QR **Definition 2.1.1.1.** The **category of spans from** A **to** B is the category $\mathsf{Span}(A, B)$ defined by

$$\mathsf{Span}(A, B) \overset{\text{def}}{=} \mathsf{Fun}(\Lambda, \mathsf{Sets}) \underset{\mathrm{ev}_{[-1]}, \mathsf{Sets}, [A]}{\times} \mathrm{pt} \underset{[B], \mathsf{Sets}, \mathrm{ev}_{[1]}}{\times} \mathsf{Fun}(\Lambda, \mathsf{Sets}),$$

as in the diagram

$$\begin{tikzcd}
 & & \mathsf{Span}(A, B) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner" very near start] & & \\
 & \mathsf{Fun}(\Lambda, \mathsf{Sets}) \underset{\mathsf{Sets}}{\times} \mathrm{pt} \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner" very near start] & & \mathrm{pt} \underset{\mathsf{Sets}}{\times} \mathsf{Fun}(\Lambda, \mathsf{Sets}) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner" very near start] & \\
\mathsf{Fun}(\Lambda, \mathsf{Sets}) \arrow[dr, "\mathrm{ev}_{[-1]}"'] & & \mathrm{pt} \arrow[dl, "{[A]}"] \arrow[dr, "{[B]}"'] & & \mathsf{Fun}(\Lambda, \mathsf{Sets}). \arrow[dl, "\mathrm{ev}_{[1]}"] \\
 & \mathsf{Sets} & & \mathsf{Sets} &
\end{tikzcd}$$

00QS **Remark 2.1.1.2.** In detail, the **category of spans from** A **to** B is the category $\mathsf{Span}(A, B)$ where

- *Objects.* The objects of $\mathsf{Span}(A, B)$ are spans from A to B;
- *Morphisms.* The morphism of $\mathsf{Span}(A, B)$ are morphisms of spans;
- *Identities.* The unit map

$$\mathbb{1}^{\mathsf{Span}(A,B)}_{(S,f,g)} \colon \mathrm{pt} \longrightarrow \mathrm{Hom}_{\mathsf{Span}(A,B)}((S, f, g), (S, f, g))$$

of $\mathsf{Span}(A,B)$ at (S,f,g) is defined by[6]

$$\mathrm{id}^{\mathsf{Span}(A,B)}_{(S,f,g)} \overset{\mathrm{def}}{=} \mathrm{id}_S;$$

- *Composition.* The composition map

$$\circ^{\mathsf{Span}(A,B)}_{R,S,T} \colon \mathrm{Hom}_{\mathsf{Span}(A,B)}(S,T) \times \mathrm{Hom}_{\mathsf{Span}(A,B)}(R,S) \to \mathrm{Hom}_{\mathsf{Span}(A,B)}(R,T)$$

  of $\mathsf{Span}(A,B)$ at $((R,f_1,g_1),(S,f_2,g_2),(T,f_3,g_3))$ is defined by[7]

$$\psi \circ^{\mathsf{Span}(A,B)}_{R,S,T} \phi \overset{\mathrm{def}}{=} \psi \circ \phi.$$

00QT 2.2 The Bicategory of Spans

00QU **Definition 2.2.1.1.** The **bicategory of spans** is the bicategory Span where

- *Objects.* The objects of Span are sets;
- Hom-*Categories.* For each $A, B \in \mathrm{Obj}(\mathsf{Span})$, we have

$$\mathrm{Hom}_{\mathsf{Span}}(A,B) \overset{\mathrm{def}}{=} \mathsf{Span}(A,B);$$

[6] *Picture:*

$$\begin{tikzcd}
 & S \arrow[dl, "f"'] \arrow[dr, "g"] \arrow[rrr, "\mathrm{id}_S"] & & & S \arrow[dl, "f"'] \arrow[dr, "g"] & \\
A \arrow[rrr, equal] & & B \arrow[rrr, equal] & A & & B.
\end{tikzcd}$$

[7] *Picture:*

$$\begin{tikzcd}
 & R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] \arrow[rrr, "\phi"] & & & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] \arrow[rrr, "\psi"] & & & T \arrow[dl, "f_3"'] \arrow[dr, "g_3"] & \\
A \arrow[rrr, equal] & & B \arrow[rrr, equal] & A \arrow[rrr, equal] & & B \arrow[rrr, equal] & A & & B.
\end{tikzcd}$$

- *Identities.* For each $A \in \mathrm{Obj}(\mathsf{Span})$, the unit functor

$$\mathbb{1}^{\mathsf{Span}}_{A} \colon \mathrm{pt} \to \mathsf{Span}(A, A)$$

of Span at A is the functor picking the span $(A, \mathrm{id}_A, \mathrm{id}_A)$:

$$\begin{tikzcd} & A \arrow[dl, "\mathrm{id}_A"'] \arrow[dr, "\mathrm{id}_A"] & \\ A & & A. \end{tikzcd}$$

- *Composition.* For each $A, B, C \in \mathrm{Obj}(\mathsf{Span})$, the composition bifunctor

$$\circ^{\mathsf{Span}}_{A,B,C} \colon \mathsf{Span}(B, C) \times \mathsf{Span}(A, B) \to \mathsf{Span}(A, C)$$

of Span at (A, B, C) is the bifunctor where

  – *Action on Objects.* The composition of two spans

$$\begin{tikzcd} & R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] & & & & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] & \\ A & & B & \text{and} & B & & C \end{tikzcd}$$

  is the span $(R \times_B S, f_1 \circ \mathrm{pr}_1, g_2 \circ \mathrm{pr}_2)$, constructed as in the diagram

$$\begin{tikzcd} & & R \times_B S \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[dd, phantom, "\lrcorner" rotate=-45, very near start] \arrow[ddll, bend right, "f_1 \circ \mathrm{pr}_1"'] \arrow[ddrr, bend left, "g_2 \circ \mathrm{pr}_2"] & & \\ & R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] & & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] & \\ A & & B & & C. \end{tikzcd}$$

  – *Action on Morphisms.* The horizontal composition of 2-morphisms is defined via functoriality of pullbacks: given morphisms of spans

$$\begin{tikzcd} & R \arrow[dl, "f"'] \arrow[dr, "g"] \arrow[dd, "\phi"] & & & & S \arrow[dl, "h"'] \arrow[dr, "k"] \arrow[dd, "\psi"] & \\ A & & B & \text{and} & B & & C, \\ & R' \arrow[ul, "f'"] \arrow[ur, "g'"'] & & & & S' \arrow[ul, "h'"] \arrow[ur, "k'"'] & \end{tikzcd}$$

their horizontal composition is the morphism of spans

$$\begin{tikzcd}
& R \times_B S \arrow[dl, "f\circ \mathrm{pr}_1"'] \arrow[dr, "k\circ \mathrm{pr}_2"] \arrow[dd, dashed, "\exists!" description] & \\
A & & C, \\
& R' \times_B S' \arrow[ul, "h'\circ \mathrm{pr}'_1"] \arrow[ur, "k'\circ \mathrm{pr}'_2"'] &
\end{tikzcd}$$

constructed as in the diagram

$$\begin{tikzcd}
& & R \times_B S \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[ddll, bend right, "f\circ \mathrm{pr}_1"'] \arrow[ddrr, bend left, "k\circ \mathrm{pr}_2"] \arrow[dddd, dashed, bend right=10, "\exists!"'] \arrow[dd, phantom, very near start, "\lrcorner", rotate=-45] & & \\
& R \arrow[dl, "f"'] \arrow[dr, "g"] & & S \arrow[dl, "h"'] \arrow[dr, "k"] & \\
A & & B & & C; \\
& R' \arrow[ul, "f'"] \arrow[ur, "g'"'] & & S' \arrow[ul, "h'"] \arrow[ur, "k'"'] & \\
& & R' \times_B S' \arrow[ul, "\mathrm{pr}'_1"] \arrow[ur, "\mathrm{pr}'_2"'] \arrow[uull, bend left, "f'\circ \mathrm{pr}'_1"] \arrow[uurr, bend right, "k'\circ \mathrm{pr}'_2"'] \arrow[uu, phantom, very near start, "\ulcorner", rotate=45] & &
\end{tikzcd}$$

- *Associators and Unitors.* The associator and unitors are defined using the universal property of the pullback.

00QV 2.3 The Monoidal Bicategory of Spans

00QW 2.4 The Double Category of Spans

00QX **Definition 2.4.1.1.** The **double category of spans** is the double category $\mathrm{Span}^{\mathrm{dbl}}$ where

- *Objects.* The objects of $\mathrm{Span}^{\mathrm{dbl}}$ are sets;

- *Vertical Morphisms.* The vertical morphisms of $\mathsf{Span}^{\mathsf{dbl}}$ are functions $f\colon A \to B$;
- *Horizontal Morphisms.* The horizontal morphisms of $\mathsf{Span}^{\mathsf{dbl}}$ are spans $(S, \phi, \psi)\colon A \nrightarrow X$;
- *2-Morphisms.* A 2-cell

$$\begin{tikzcd}
A \arrow[r, "{(R,\phi_R,\psi_R)}", "\shortmid"{marking}] \arrow[d, "f"'] \arrow[dr, phantom, "\Downarrow\alpha"] & B \arrow[d, "g"] \\
X \arrow[r, "{(S,\phi_S,\psi_S)}"', "\shortmid"{marking}] & Y
\end{tikzcd}$$

of $\mathsf{Span}^{\mathsf{dbl}}$ is a morphism of spans from the span

$$\begin{tikzcd}
 & & R \arrow[lld, "\phi_R"'] \arrow[d, "\psi_R"] & \\
 & & B \arrow[d, "g"] & \\
A & & Y &
\end{tikzcd}$$

to the span

$$\begin{tikzcd}
 & & A \times_X S \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & & \\
 & A \arrow[dl, "f"'] \arrow[dr, "f"] & & S \arrow[dl, "\phi_S"'] \arrow[dr, "\psi_S"] & \\
X & & X & & Y;
\end{tikzcd}$$

- *Horizontal Identities.* The horizontal unit functor

$$\nVdash^{\mathsf{Span}^{\mathsf{dbl}}}\colon \left(\mathsf{Span}^{\mathsf{dbl}}\right)_0 \to \left(\mathsf{Span}^{\mathsf{dbl}}\right)_1$$

of $\mathsf{Span}^{\mathsf{dbl}}$ is the functor where

  - *Action on Objects.* For each $A \in \mathrm{Obj}\left(\left(\mathsf{Span}^{\mathsf{dbl}}\right)_0\right)$, we have

$$\nVdash_A \stackrel{\text{def}}{=} (A, \mathrm{id}_A, \mathrm{id}_A),$$

as in the diagram

$$\begin{tikzcd}
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] & \\
A & & A;
\end{tikzcd}$$

– *Action on Morphisms.* For each vertical morphism $f\colon A \to B$ of $\mathsf{Span}^{\mathsf{dbl}}$, i.e. each map of sets f from A to B, the identity 2-morphism

$$\begin{tikzcd}
A \arrow[r, "\mathbb{1}_A", "|" marking] \arrow[d, "f"'] \arrow[dr, phantom, "\Downarrow \mathbb{1}_f"] & A \arrow[d, "f"] \\
B \arrow[r, "\mathbb{1}_B"', "|" marking] & B
\end{tikzcd}$$

of f is the morphism of spans from

$$\begin{tikzcd}
 & & A \arrow[dll, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] & \\
 & & & A \arrow[d, "f"] \\
A & & & B
\end{tikzcd}$$

to

$$\begin{tikzcd}
 & & A \times_B B \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner" rotate=-45, very near start] & & \\
 & A \arrow[dl, "f"'] \arrow[dr, "f"] & & B \arrow[dl, equal, "\mathrm{id}_B"'] \arrow[dr, equal, "\mathrm{id}_B"] & \\
B & & B & & B
\end{tikzcd}$$

given by the isomorphism $A \xrightarrow{\cong} A \times_B B$;

- *Vertical Identities.* For each $A \in \mathrm{Obj}\left(\mathsf{Span}^{\mathsf{dbl}}\right)$, we have

$$\mathrm{id}_A^{\mathsf{Span}^{\mathsf{dbl}}} \stackrel{\text{def}}{=} \mathrm{id}_A;$$

- *Identity* 2*-Morphisms.* For each horizontal morphism $R\colon A \nrightarrow B$ of $\mathsf{Span}^{\mathsf{dbl}}$, the identity 2-morphism

$$\begin{tikzcd}
A \arrow[r, "S", "\shortmid"{marking}] \arrow[d, "\mathrm{id}_A"'] \arrow[dr, phantom, "\substack{\parallel \\ \mathrm{id}_S \\ \Downarrow}"] & B \arrow[d, "\mathrm{id}_B"] \\
A \arrow[r, "S"', "\shortmid"{marking}] & B
\end{tikzcd}$$

of R is the morphism of spans from

$$\begin{tikzcd}
 & S \arrow[ddl, "\phi_S"'] \arrow[d, "\psi_S"] & \\
 & B \arrow[dr, equal, "\mathrm{id}_B"] & \\
A & & B
\end{tikzcd}$$

to

$$\begin{tikzcd}
 & & A \times_A S \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner" rotate=-45, very near start] & & \\
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] & & S \arrow[dl, "\phi_S"'] \arrow[dr, "\psi_S"] & \\
A & & A & & B
\end{tikzcd}$$

given by the isomorphism $S \xrightarrow{\cong} A \times_A S$;

- *Horizontal Composition.* The horizontal composition functor

$$\odot^{\mathsf{Span}^{\mathsf{dbl}}} \colon \left(\mathsf{Span}^{\mathsf{dbl}}\right)_1 \times_{\left(\mathsf{Span}^{\mathsf{dbl}}\right)_0} \left(\mathsf{Span}^{\mathsf{dbl}}\right)_1 \to \left(\mathsf{Span}^{\mathsf{dbl}}\right)_1$$

of $\mathsf{Span}^{\mathsf{dbl}}$ is the functor where

  - *Action on Objects.* For each composable pair

$$A \overset{(R,\phi_R,\psi_R)}{\nrightarrow} B \overset{(S,\phi_S,\psi_S)}{\nrightarrow} C$$

of horizontal morphisms of $\mathsf{Span}^{\mathsf{dbl}}$, we have

$$(S, \phi_S, \psi_S) \odot (R, \phi_R, \psi_R) \overset{\mathrm{def}}{=} S \circ^{\mathsf{Span}}_{A,B,C} R,$$

where $S \circ^{\mathsf{Span}}_{A,B,C} R$ is the composition of (R, ϕ_R, ψ_R) and (S, ϕ_S, ψ_S) defined as in Definition 2.2.1.1;

– *Action on Morphisms.* For each horizontally composable pair

$$\begin{tikzcd} A \arrow[r, "{(R,\phi_R,\psi_R)}", "|" marking] \arrow[d, "f"'] \arrow[dr, phantom, "\Downarrow\alpha"] & B \arrow[d, "g"] \\ X \arrow[r, "{(T,\phi_T,\psi_T)}"', "|" marking] & Y \end{tikzcd} \qquad \begin{tikzcd} B \arrow[r, "{(S,\phi_S,\psi_S)}", "|" marking] \arrow[d, "g"'] \arrow[dr, phantom, "\Downarrow\beta"] & C \arrow[d, "h"] \\ Y \arrow[r, "{(U,\phi_U,\psi_U)}"', "|" marking] & Z \end{tikzcd}$$

of 2-morphisms of $\mathsf{Span}^{\mathsf{dbl}}$,

- *Vertical Composition of* 1*-Morphisms.* For each composable pair $A \xrightarrow{F} B \xrightarrow{G} C$ of vertical morphisms of $\mathsf{Span}^{\mathsf{dbl}}$, i.e. maps of sets, we have

$$g \circ^{\mathsf{Span}^{\mathsf{dbl}}} f \overset{\mathrm{def}}{=} g \circ f;$$

- *Vertical Composition of* 2*-Morphisms.* For each vertically composable pair

$$\begin{tikzcd} A \arrow[r, "{(R,\phi_R,\psi_R)}", "|" marking] \arrow[d, "f"'] \arrow[dr, phantom, "\Downarrow\alpha"] & X \arrow[d, "g"] \\ B \arrow[r, "{(S,\phi_S,\psi_S)}"', "|" marking] & Y \end{tikzcd} \qquad \begin{tikzcd} B \arrow[r, "{(S,\phi_S,\psi_S)}", "|" marking] \arrow[d, "h"'] \arrow[dr, phantom, "\Downarrow\beta"] & Y \arrow[d, "k"] \\ C \arrow[r, "{(T,\phi_T,\psi_T)}"', "|" marking] & Z \end{tikzcd}$$

of 2-morphisms of $\mathsf{Span}^{\mathsf{dbl}}$,

- *Associators and Unitors.* The associator and unitors of $\mathsf{Span}^{\mathsf{dbl}}$ are defined using the universal property of the pullback.

00QY 2.5 Properties of The Bicategory of Spans

00QZ **Proposition 2.5.1.1.** Let $\lambda = \left(A \overset{f}{\leftarrow} S \overset{g}{\rightarrow} B\right)$ be a span.

00R0 1. *Self-Duality.*

00R1 2. *Isomorphisms in* Span.

00R2 3. *Equivalences in* Span.

00R3 4. *Adjunctions in* Span. Let A and B be sets.[8]

[8] In the literature (e.g. [**ref**]),…are called maps and denoted by $\mathsf{MapSpan}(A, B)$

00R4 (a) We have a natural bijection

$$\left\{\begin{matrix}\text{Adjunctions in Span}\\ \text{from } A \text{ to } B\end{matrix}\right\} \cong \left\{\begin{matrix}\text{Spans } A \xleftarrow{f} S \xrightarrow{g} B\\ \text{from } A \text{ to } B \text{ with}\\ f \text{ an isomorphism}\end{matrix}\right\}.$$

00R5 (b) We have an equivalence of categories

$$\mathsf{MapSpan}(A, B) \overset{\text{eq.}}{\cong} \mathsf{Sets}(A, B)_{\mathsf{disc}},$$

where $\mathsf{MapSpan}(A, B)$ is the full subcategory of $\mathsf{Span}(A, B)$ spanned by the spans $A \xleftarrow{f} S \xrightarrow{g} B$ from A to B with f an isomorphism.

00R6 (c) We have a biequivalence of bicategories

$$\mathsf{MapSpan} \overset{\text{eq.}}{\cong} \mathsf{Sets}_{\mathsf{bidisc}},$$

where MapSpan is the sub-bicategory of Span whose Hom-categories are given by $\mathsf{MapSpan}(A, B)$.

00R7 5. *Monads in* Span.

00R8 6. *Comonads in* Span.

00R9 7. *Monomorphisms in* Span.

00RA 8. *Epimorphisms in* Span.

00RB 9. *Existence of Right Kan Extensions.*

00RC 10. *Existence of Right Kan Lifts.*

00RD 11. *Closedness.*

Proof. Item 1, *Self-Duality*:
Item 2, *Isomorphisms in* Span:
Item 3, *Equivalences in* Span:
Item 4, *Adjunctions in* Span: We first prove Item 4a.
We proceed step by step:

1. *From Adjunctions in* Span *to Functions.* An adjunction in Span from A to B consists of a pair of spans

$$\begin{tikzcd} & R \arrow[dl, "f"'] \arrow[dr, "g"] & \\ A & & B \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} & S' \arrow[dl, "h"'] \arrow[dr, "k"] & \\ B & & A \end{tikzcd}$$

together with maps

$$
\begin{tikzcd}
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] \arrow[d, dash] & \\
A & \phi \arrow[d] & A \\
 & S \times_B S' \arrow[ul, "f\circ\mathrm{pr}'_1"] \arrow[ur, "k\circ\mathrm{pr}'_2"'] &
\end{tikzcd}
\quad \text{and} \quad
\begin{tikzcd}
 & S' \times_A S \arrow[dl, "h\circ\mathrm{pr}_1"'] \arrow[dr, "g\circ\mathrm{pr}_2"] \arrow[d, dash] & \\
B \arrow[dr, equal, "\mathrm{id}_B"'] & \psi \arrow[d] & B. \arrow[dl, equal, "\mathrm{id}_B"] \\
 & B &
\end{tikzcd}
$$

We claim that these conditions

2. *From Functions to Adjunctions in* **Rel**.
3. *Invertibility: From Functions to Adjunctions Back to Functions.*
4. *Invertibility: From Adjunctions to Functions Back to Adjunctions.*

We now proceed to the proof of Item 4b. For this, we will construct a functor

$$F\colon \mathsf{Sets}(A,B)_{\mathsf{disc}} \longrightarrow \mathsf{MapSpan}(A,B)$$

and prove it to be essentially surjective and fully faithful, and thus an equivalence by Categories, **??** of **??**. Indeed, given a map $f\colon A \longrightarrow B$, let $F(f)$ be the representable span associated to f of Definition 5.1.1.1, and let F send the unique (identity) morphism from f to itself to the identity morphism of $F(f)$ in $\mathsf{MapSpan}(A,B)$. We now prove that F is fully faithful and essentially surjective:

1. *F Is Fully Faithful:* Given maps $f, g\colon A \rightrightarrows B$, we need to show that

$$\mathrm{Hom}_{\mathsf{MapSpan}(A,B)}(F(f), F(g)) = \begin{cases} \mathrm{pt} & \text{if } f = g, \\ \emptyset & \text{otherwise.} \end{cases}$$

Indeed, a morphism from $F(f)$ to $F(g)$ takes the form

$$
\begin{tikzcd}
 & A \arrow[dl, equal] \arrow[dr, "f"] \arrow[d, dash] & \\
A & \phi \arrow[d] & B. \\
 & A \arrow[ul, equal] \arrow[ur, "g"'] &
\end{tikzcd}
$$

From the relations $\mathrm{id}_A = \mathrm{id}_A \circ \phi$ and $f = g \circ \phi$, we see that $\phi = \mathrm{id}_A$, and thus from the relation $f = g \circ \phi$ there is such a morphism iff $f = g$.

2. *F Is Essentially Surjective:* Let λ be a span of the form

$$\begin{tikzcd} & S \arrow[dl, dashed, "\phi"', "\sim"] \arrow[dr, "f"] & \\ A & & B. \end{tikzcd}$$

we claim that $\lambda \cong F(f \circ \phi^{-1})$. Indeed, we have morphisms

$$\begin{tikzcd} & S \arrow[dl, dashed, "\phi"', "\sim"] \arrow[dr, "f"] \arrow[dd, "\phi"] & \\ A \arrow[dr, equal] & & B \\ & A \arrow[ur, "f\circ\phi^{-1}"'] & \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} & A \arrow[dl, equal] \arrow[dr, "f\circ\phi^{-1}"] \arrow[dd, "\phi^{-1}"] & \\ A & & B, \\ & S \arrow[ul, dashed, "\phi", "\sim"'] \arrow[ur, "f"'] & \end{tikzcd}$$

inverse to each other in $\mathsf{MapSpan}(A, B)$, and thus $\lambda \cong F(f \circ \phi^{-1})$.

Finally, we prove Item 4c.

Item 5, Monads in Span:

Item 6, Comonads in Span:

Item 7, Monomorphisms in Span:

Item 8, Epimorphisms in Span:

Item 9, Existence of Right Kan Extensions:

Item 10, Existence of Right Kan Lifts:

Item 11, Closedness:

□

00RE 3 Limits of Spans

00RF 4 Colimits of Spans

00RG 5 Constructions With Spans

00RH 5.1 Representable Spans

00RJ **Definition 5.1.1.1.** Let $f : A \longrightarrow B$ be a function.

- The **representable span associated to** f is the span

$$\begin{tikzcd} & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, "f"] & \\ A & & B \end{tikzcd}$$

from A to B.

- The **corepresentable span associated to** f is the span

$$\begin{tikzcd} & A \arrow[dl, "f"'] \arrow[dr, equal, "\mathrm{id}_A"] & \\ B & & A \end{tikzcd}$$

from B to A.

00RK 5.2 Composition of Spans

00RL **Definition 5.2.1.1.** The **composition** of two spans

$$\begin{tikzcd} & R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] & \\ A & & B \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] & \\ B & & C \end{tikzcd}$$

is the span $(R \times_B S, f_1 \circ \mathrm{pr}_1, g_2 \circ \mathrm{pr}_2)$, constructed as in the diagram

$$\begin{tikzcd} & & R \times_B S \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[dd, phantom, very near start, "\lrcorner"] \arrow[ddll, bend right, "f_1 \circ \mathrm{pr}_1"'] \arrow[ddrr, bend left, "g_2 \circ \mathrm{pr}_2"] & & \\ & R \arrow[dl, "f_1"'] \arrow[dr, "g_1"] & & S \arrow[dl, "f_2"'] \arrow[dr, "g_2"] & \\ A & & B & & C. \end{tikzcd}$$

00RM 5.3 Horizontal Composition of Morphisms of Spans

00RN **Definition 5.3.1.1.** The **horizontal composition** of a pair of 2-morphisms of spans

$$\begin{tikzcd} & R \arrow[dl, "f"'] \arrow[dr, "g"] \arrow[dd, "\phi"] & \\ A & & B \\ & R' \arrow[ul, "f'"] \arrow[ur, "g'"'] & \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} & S \arrow[dl, "h"'] \arrow[dr, "k"] \arrow[dd, "\psi"] & \\ B & & C, \\ & S' \arrow[ul, "h'"] \arrow[ur, "k'"'] & \end{tikzcd}$$

is the morphism of spans

$$\begin{tikzcd}
 & R \times_B S \arrow[dl, "f \circ \mathrm{pr}_1"'] \arrow[dr, "k \circ \mathrm{pr}_2"] \arrow[dd, dashed, "\exists!"] & \\
A & & C, \\
 & R' \times_B S' \arrow[ul, "h' \circ \mathrm{pr}'_1"] \arrow[ur, "k' \circ \mathrm{pr}'_2"'] &
\end{tikzcd}$$

constructed as in the diagram

$$\begin{tikzcd}
 & & R \times_B S \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[dll, bend right, "f \circ \mathrm{pr}_1"'] \arrow[drr, bend left, "k \circ \mathrm{pr}_2"] \arrow[dddd, dashed, bend right=15, "\exists!"'] \arrow[dd, phantom, "\lrcorner" rotate=-45, very near start] & & \\
 & R \arrow[dl, "f"'] \arrow[dr, "g"] & & S \arrow[dl, "h"'] \arrow[dr, "k"] & \\
A & & B & & C; \\
 & R' \arrow[ul, "f'"] \arrow[ur, "g'"'] & & S' \arrow[ul, "h'"] \arrow[ur, "k'"'] & \\
 & & R' \times_B S' \arrow[ul, "\mathrm{pr}'_1"] \arrow[ur, "\mathrm{pr}'_2"'] \arrow[ull, bend left, "f' \circ \mathrm{pr}'_1"] \arrow[urr, bend right, "k' \circ \mathrm{pr}'_2"'] \arrow[uu, phantom, "\ulcorner" rotate=45, very near start] & &
\end{tikzcd}$$

00RP 5.4 Properties of Composition of Spans

00RQ **Proposition 5.4.1.1.** Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B\right)$ be a span.

00RR 1. *Functoriality.*

Proof. □

00RS 5.5 The Inverse of a Span

00RT 6 Functoriality of Spans

00RU 6.1 Direct Images

00RV 6.2 Functoriality of Spans on Powersets

00RW 7 Comparison of Spans to Functions and Relations

00RX 7.1 Comparison to Functions

00RY **Proposition 7.1.1.1.** We have a pseudofunctor

$$\iota\colon \mathsf{Sets}_{\mathsf{bidisc}} \to \mathsf{Span}$$

from $\mathsf{Sets}_{\mathsf{bidisc}}$ to Span where

- *Action on Objects.* For each $A \in \mathrm{Obj}(\mathsf{Sets}_{\mathsf{bidisc}})$, we have

$$\iota(A) \overset{\text{def}}{=} A;$$

- *Action on* Hom*-Categories.* For each $A, B \in \mathrm{Obj}(\mathsf{Sets}_{\mathsf{bidisc}})$, the action on Hom-categories

$$\iota_{A,B}\colon \mathsf{Sets}(A,B)_{\mathsf{disc}} \to \mathsf{Span}(A,B)$$

  of ι at (A,B) is the functor defined on objects by sending a function $f\colon A \to B$ to the span

$$\begin{tikzcd} & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, "f"] & \\ A & & B \end{tikzcd}$$

  from A to B.

- *Strict Unity Constraints.* For each $A \in \mathrm{Obj}(\mathsf{Sets}_{\mathsf{bidisc}})$, the strict unity constraint

$$\iota^0_A\colon \mathrm{id}_{\iota(A)} \Longrightarrow \iota(\mathrm{id}_A)$$

  of ι at A is given by the identity morphism of spans

$$\begin{tikzcd} & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] \arrow[dd, equal, "\mathrm{id}"] & \\ A & & A, \\ & A \arrow[ul, equal, "\mathrm{id}_A"] \arrow[ur, equal, "\mathrm{id}_A"'] & \end{tikzcd}$$

  as indeed $\mathrm{id}_{\iota(A)} = \iota(\mathrm{id}_A)$;

- *Pseudofunctoriality Constraints.* For each $A, B, C \in \mathrm{Obj}(\mathsf{Sets}_{\mathsf{bidisc}})$, each $f \in \mathrm{Hom}_{\mathsf{Sets}_{\mathsf{bidisc}}}(A, B)$, and each $g \in \mathrm{Hom}_{\mathsf{Sets}_{\mathsf{bidisc}}}(B, C)$, the pseudofunctoriality constraint

$$\iota^2_{g,f} \colon \iota(g) \circ \iota(f) \Longrightarrow \iota(g \circ f)$$

of ι at (f, g) is the morphism of spans from the span

$$\begin{tikzcd}
 & & A \times_B B \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[dd, phantom, very near start, "\lrcorner" rotate=-45] \arrow[ddll, bend right, "\mathrm{id}_A \circ \mathrm{pr}_1"'] \arrow[ddrr, bend left, "g \circ \mathrm{pr}_2"] & & \\
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, "f"] & & B \arrow[dl, equal, "\mathrm{id}_B"'] \arrow[dr, "g"] & \\
A & & B & & C.
\end{tikzcd}$$

to the span

$$\begin{tikzcd}
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, "g \circ f"] & \\
A & & C
\end{tikzcd}$$

given by the isomorphism $A \times_B B \cong A$.

Proof. Omitted. □

00RZ 7.2 Comparison to Relations: From Span to Rel

00S0 7.2.1 Relations Associated to Spans

Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B\right)$ be a span.

00S1 **Definition 7.2.1.1.** The **relation associated to** λ is the relation

$$S(\lambda) \colon A \nrightarrow B$$

from A to B defined as follows:

- Viewing relations from A to B as functions $A \times B \to \{\mathrm{true}, \mathrm{false}\}$, we define

$$\iota_{A,B}(S)^a_b \overset{\mathrm{def}}{=} \begin{cases} \mathrm{true} & \text{if there exists } x \in S \text{ such} \\ & \text{that } a = f(x) \text{ and } b = g(x), \\ \mathrm{false} & \text{otherwise} \end{cases}$$

for each $(a, b) \in A \times B$.

- Viewing relations from A to B as functions $A \to \mathcal{P}(B)$, we define

$$[\iota_{A,B}(S)](a) \stackrel{\text{def}}{=} g(f^{-1}(a))$$

for each $a \in A$.

- Viewing relations from A to B as subsets of $A \times B$, we define

$$\iota_{A,B}(S) \stackrel{\text{def}}{=} \{(f(x), g(x)) \mid x \in S\}.$$

00S2 **Proposition 7.2.1.2.** Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B\right)$ be a span.

00S3 1. *Interaction With Identities.*

00S4 2. *Interaction With Composition.*

00S5 3. *Interaction With Inverses.*

Proof. □

00S6 ### 7.2.2 The Comparison Functor from Span to Rel

00S7 **Proposition 7.2.2.1.** We have a pseudofunctor

$$\iota\colon \mathsf{Span} \to \mathbf{Rel}$$

from Span to **Rel** where

- *Action on Objects.* For each $A \in \mathrm{Obj}(\mathsf{Span})$, we have

$$\iota(A) \stackrel{\text{def}}{=} A;$$

- *Action on* Hom*-Categories.* For each $A, B \in \mathrm{Obj}(\mathsf{Span})$, the action on Hom-categories

$$\iota_{A,B}\colon \mathsf{Span}(A, B) \to \mathbf{Rel}(A, B)$$

of ι at (A, B) is the functor where

  - *Action on Objects.* Given a span

$$\begin{tikzcd} & S \arrow[dl, "f"'] \arrow[dr, "g"] & \\ A & & B \end{tikzcd}$$

from A to B, the image

$$\iota_{A,B}(S)\colon A \nrightarrow B$$

of S by ι is the relation from A to B defined as follows:

- Viewing relations as functions $A \times B \to \{\text{true}, \text{false}\}$, we define

$$\iota_{A,B}(S)^a_b \overset{\text{def}}{=} \begin{cases} \text{true} & \text{if there exists } x \in S \\ & \text{such that } a = f(x) \\ & \text{and } b = g(x), \\ \text{false} & \text{otherwise} \end{cases}$$

for each $(a, b) \in A \times B$;
- Viewing relations as functions $A \to \mathcal{P}(B)$, we define

$$[\iota_{A,B}(S)](a) \overset{\text{def}}{=} g(f^{-1}(a))$$

for each $a \in A$;
- Viewing relations as subsets of $A \times B$, we define

$$\iota_{A,B}(S) \overset{\text{def}}{=} \{(f(x), g(x)) \mid x \in S\}.$$

– *Action on Morphisms.* Given a morphism of spans

$$\begin{tikzcd} & R \arrow[dl, "f_R"'] \arrow[dr, "g_R"] \arrow[dd, "\phi"] & \\ A & & B, \\ & S \arrow[ul, "f_S"] \arrow[ur, "g_S"'] & \end{tikzcd}$$

we have a corresponding inclusion of relations

$$\iota_{A,B}(\phi) \colon \iota_{A,B}(R) \subset \iota_{A,B}(S),$$

since we have $a \sim_{\iota_{A,B}(R)} b$ iff there exists $x \in R$ such that $a = f_R(x)$ and $b = g_R(x)$, in which case we then have

$$\begin{aligned} a &= f_R(x) \\ &= f_S(\phi(x)), \\ b &= g_R(x) \\ &= g_S(\phi(x)), \end{aligned}$$

so that $a \sim_{\iota_{A,B}(S)} b$, and thus $\iota_{A,B}(R) \subset \iota_{A,B}(S)$.

Proof. Omitted. □

00S8 7.3 Comparison to Relations: From Rel to Span

00S9 **Proposition 7.3.1.1.** We have a lax functor

$$\left(\iota, \iota^2, \iota^0\right) \colon \mathbf{Rel} \to \mathsf{Span}$$

from **Rel** to Span where

- *Action on Objects.* For each $A \in \mathrm{Obj}(\mathsf{Span})$, we have

$$\iota(A) \overset{\text{def}}{=} A;$$

- *Action on* Hom*-Categories.* For each $A, B \in \mathrm{Obj}(\mathsf{Span})$, the action on Hom-categories

$$\iota_{A,B} \colon \mathbf{Rel}(A, B) \to \mathsf{Span}(A, B)$$

  of ι at (A, B) is the functor where

  – *Action on Objects.* Given a relation $R \colon A \mathrel{+\!\!\!\!\to} B$ from A to B, we define a span

$$\iota_{A,B}(R) \colon A \mathrel{+\!\!\!\!\to} B$$

  from A to B by

$$\iota_{A,B}(R) \overset{\text{def}}{=} (R, \restriction \mathrm{pr}_1 R, \restriction \mathrm{pr}_2 R),$$

  where $R \subset A \times B$ and $\restriction \mathrm{pr}_1 R$ and $\restriction \mathrm{pr}_2 R$ are the restriction of the projections

$$\begin{aligned} \mathrm{pr}_1 &\colon A \times B \to A, \\ \mathrm{pr}_2 &\colon A \times B \to B \end{aligned}$$

  to R;

  – *Action on Morphisms.* Given an inclusion $\phi \colon R \subset S$ of relations, we have a corresponding morphism of spans

$$\iota_{A,B}(\phi) \colon \iota_{A,B}(R) \to \iota_{A,B}(S)$$

  as in the diagram

$$\begin{tikzcd}
 & R \arrow[dl, "\restriction \mathrm{pr}_1 R"'] \arrow[dr, "\restriction \mathrm{pr}_2 R"] \arrow[dd, hook] & \\
A & & B. \\
 & S \arrow[ul, "\restriction \mathrm{pr}_1 S"] \arrow[ur, "\restriction \mathrm{pr}_2 S"'] &
\end{tikzcd}$$

- *The Lax Functoriality Constraints.* The lax functoriality constraint

$$\iota^2_{R,S} \colon \iota(S) \circ \iota(R) \Longrightarrow \iota(S \diamond R)$$

of ι at (R, S) is given by the morphism of spans from

$$\begin{tikzcd}
 & & R \times_B S \arrow[dl, "\mathrm{pr}_1"'] \arrow[dr, "\mathrm{pr}_2"] \arrow[dd, phantom, very near start, "\vee"] \arrow[ddll, bend right, "\upharpoonright\mathrm{pr}_1 R \circ \mathrm{pr}_1"'] \arrow[ddrr, bend left, "\upharpoonright\mathrm{pr}_2 S \circ \mathrm{pr}_2"] & & \\
 & R \arrow[dl, "\upharpoonright\mathrm{pr}_1 R"'] \arrow[dr, "\upharpoonright\mathrm{pr}_2 R"] & & S \arrow[dl, "\upharpoonright\mathrm{pr}_1 S"'] \arrow[dr, "\upharpoonright\mathrm{pr}_2 S"] & \\
A & & B & & C
\end{tikzcd}$$

to

$$\begin{tikzcd}
 & S \diamond R \arrow[dl, "\upharpoonright\mathrm{pr}_1 S \diamond R"'] \arrow[dr, "\upharpoonright\mathrm{pr}_2 S \diamond R"] & \\
A & & C
\end{tikzcd}$$

given by the natural inclusion $R \times_B S \hookrightarrow S \diamond R$, since we have

$$\begin{aligned}
R \times_B S &= \{((a_R, b_R), (b_S, c_S)) \in R \times S \mid b_R = b_S\}; \\
S \diamond R &= \left\{ (a, c) \in A \times C \,\middle|\, \begin{array}{l} \text{there exists some } b \in B \text{ such that} \\ (a, b) \in R \text{ and } (b, c) \in S \end{array} \right\};
\end{aligned}$$

- *The Lax Unity Constraints.* The lax unity constraint[9]

$$\iota^0_A \colon \quad \underbrace{\mathrm{id}_{\iota(A)}}_{(A, \mathrm{id}_A, \mathrm{id}_A)} \quad \Longrightarrow \quad \underbrace{\iota(\chi_A)}_{(\Delta_A, \upharpoonright\mathrm{pr}_1 \Delta_A, \upharpoonright\mathrm{pr}_2 \Delta_A)}$$

of ι at A is given by the diagonal morphism of A, as in the diagram

$$\begin{tikzcd}
 & A \arrow[dl, equal, "\mathrm{id}_A"'] \arrow[dr, equal, "\mathrm{id}_A"] \arrow[dd, "\delta_A"] & \\
A & & A. \\
 & \Delta_A \arrow[ul, "\upharpoonright\mathrm{pr}_1 \Delta_A"] \arrow[ur, "\upharpoonright\mathrm{pr}_2 \Delta_A"'] &
\end{tikzcd}$$

Proof. Omitted. □

[9] Which is in fact strong, as δ_A is an isomorphism.

00SA 7.4 Comparison to Relations: The Wehrheim–Woodward Construction

00SB 7.5 Comparison to Multirelations

00SC **Remark 7.5.1.1.** The pseudofunctor of Proposition 7.2.2.1 and the lax functor of Proposition 7.3.1.1 fail to be equivalences of bicategories. This happens essentially because a span $(S, f, g) \colon A \nrightarrow B$ from A to B may relate elements $a \in A$ and $b \in B$ by more than one element, e.g. there could be $s \neq s' \in S$ such that $a = f(s) = f(s')$ and $b = g(s) = g(s')$.
Thus, in a sense, spans may be thought of as "relations with multiplicity". And indeed, if instead of considering relations from A to B, i.e. functions

$$R \colon A \times B \to \{\text{true}, \text{false}\}$$

from $A \times B$ to $\{\text{true}, \text{false}\} \cong \{0, 1\}$, we consider functions

$$R \colon A \times B \to \mathbb{N} \cup \{\infty\}$$

from $A \times B$ to $\mathbb{N} \cup \{\infty\}$, then we obtain the notion of a **multirelation from A to B**, and these turn out to assemble together with sets into a bicategory MRel that is biequivalent to Span; see [**some-algebraic-laws-for-spans-and-their-connections-with-multirelations**].

00SD 7.6 Comparison to Relations via Double Categories

00SE **Remark 7.6.1.1.** There are double functors between the double categories $\mathsf{Rel}^{\mathsf{dbl}}$ and $\mathsf{Span}^{\mathsf{dbl}}$ analogous to the functors of Propositions 7.2.2.1 and 7.3.1.1, assembling moreover into a strict-lax adjunction of double functors; see [**higher-dimensional-categories**].

Appendices

A Other Chapters