Ptolemy’s Theorem

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Abstract

This entry provides an analytic proof to Ptolemy’s Theorem using polar form transformation and trigonometric identities. In this formalization, we use ideas from John Harrison’s HOL Light formalization [1] and the proof sketch on the Wikipedia entry of Ptolemy’s Theorem [3]. This theorem is the 95th theorem of the Top 100 Theorems list [2].

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1 Ptolemy’s Theorem

theory Ptolemys-Theorem
imports
   HOL—Analysis.Multivariate-Analysis
begin

1.1 Preliminaries

1.1.1 Additions to Rat theory

hide-const (open) normalize
1.1.2 Additions to Transcendental theory

Lemmas about \( \arcsin \) and \( \arccos \) commonly involve to show that their argument is in the domain of those partial functions, i.e., the argument \( y \) is between \(-1\) and \(1\). As the argumentation for \(-1 \leq y \) and \( y \leq 1 \) is often very similar, we prefer to prove \(|y| \leq 1\) to the two goals above.

The lemma for rewriting the term \( \cos (\arccos y) \) is already provided in the Isabelle distribution with name \( \text{cos-arccos-abs} \). Here, we further provide the analogue on \( \arcsin \) for rewriting \( \sin (\arcsin y) \).

\textbf{lemma} \( \text{sin-arcsin-abs} \): \(|y| \leq 1 \implies \sin (\arcsin y) = y\)

The further lemmas are the required variants from existing lemmas \( \text{arccos-lbound} \) and \( \text{arccos-ubound} \).

\textbf{lemma} \( \text{arccos-lbound-abs} \) [simp]:
\(|y| \leq 1 \implies 0 \leq \arccos y\)

\textbf{lemma} \( \text{arccos-ubound-abs} \) [simp]:
\(|y| \leq 1 \implies \arccos y \leq \pi\)

As we choose angles to be between \(0\) between \(2 \cdot \pi\), we need some lemmas to reason about the sign of \( \sin x \) for angles \( x \).

\textbf{lemma} \( \text{sin-ge-zero-iff} \):
\(\begin{align*}
&\text{assumes } 0 \leq x \land x < 2 \cdot \pi \\
&\text{shows } 0 \leq \sin x \iff x \leq \pi
\end{align*}\)

\textbf{lemma} \( \text{sin-less-zero-iff} \):
\(\begin{align*}
&\text{assumes } 0 \leq x \land x < 2 \cdot \pi \\
&\text{shows } \sin x < 0 \iff \pi < x
\end{align*}\)

1.1.3 Addition to Finite-Cartesian-Product theory

Here follow generally useful additions and specialised equations for two-dimensional real-valued vectors.

\textbf{lemma} \( \text{axis-nth-eq-0} \) [simp]:
\(\begin{align*}
&\text{assumes } i \neq j \\
&\text{shows } \text{axis } i \cdot x \neq 0
\end{align*}\)

\textbf{lemma} \( \text{norm-axis} \):
\(\begin{align*}
&\text{fixes } x :: \text{real} \\
&\text{shows } \text{norm } (\text{axis } i \cdot x) = \text{abs } x
\end{align*}\)
lemma norm-eq-on-real-2-vec:
  fixes x :: real ^ 2
  shows norm x = sqrt ((x $ 1) ^ 2 + (x $ 2) ^ 2)
⟨proof⟩

lemma dist-eq-on-real-2-vec:
  fixes a b :: real ^ 2
  shows dist a b = sqrt ((a $ 1 - b $ 1) ^ 2 + (a $ 2 - b $ 2) ^ 2)
⟨proof⟩

1.2 Polar Form of Two-Dimensional Real-Valued Vectors

1.2.1 Definitions to Transfer to Polar Form and Back

definition of-radiant :: real ⇒ real ^ 2
  where
  of-radiant ω = axis 1 (cos ω) + axis 2 (sin ω)

definition normalize :: real ^ 2 ⇒ real ^ 2
  where
  normalize p = (if p = 0 then axis 1 1 else (1 / norm p) * R p)

definition radiant-of :: real ^ 2 ⇒ real
  where
  radiant-of p = (THE ω. 0 ≤ ω ∧ ω < 2 * pi ∧ of-radiant ω = normalize p)

The vector of-radiant ω is the vector with length 1 and angle ω to the first axis. We normalize vectors to length 1 keeping their orientation with the normalize function. Conversely, radiant-of p is the angle of vector p to the first axis, where we choose radiant-of to return angles between 0 and 2 * pi, following the usual high-school convention. With these definitions, we can express the main result norm p * R of-radiant (radiant-of p) = p. Note that the main result holds for any definition of radiant-of 0. So, we choose to define normalize 0 and radiant-of 0, such that radiant-of 0 = 0.

1.2.2 Lemmas on of-radiant

lemma nth-of-radiant-1 [simp]:
  of-radiant ω $ 1 = cos ω
⟨proof⟩

lemma nth-of-radiant-2 [simp]:
  of-radiant ω $ 2 = sin ω
⟨proof⟩

lemma norm-of-radiant:
  norm (of-radiant ω) = 1
⟨proof⟩
lemma of-radiant-plus-2pi:
  of-radiant (ω + 2 * pi) = of-radiant ω
 ⟨proof⟩

lemma of-radiant-minus-2pi:
  of-radiant (ω - 2 * pi) = of-radiant ω
 ⟨proof⟩

1.2.3 Lemmas on normalize

lemma normalize-eq:
  norm p *R normalize p = p
 ⟨proof⟩

lemma norm-normalize:
  norm (normalize p) = 1
 ⟨proof⟩

lemma nth-normalize [simp]:
  |normalize p $ i| ≤ 1
 ⟨proof⟩

lemma normalize-square:
  (normalize p $ 1)^2 + (normalize p $ 2)^2 = 1
 ⟨proof⟩

lemma nth-normalize-ge-zero-iff:
  0 ≤ normalize p $ i ←→ 0 ≤ p $ i
 ⟨proof⟩

lemma nth-normalize-less-zero-iff:
  normalize p $ i < 0 ←→ p $ i < 0
 ⟨proof⟩

lemma normalize-boundary-iff:
  |normalize p $ 1| = 1 ←→ p $ 2 = 0
 ⟨proof⟩

lemma between-normalize-if-distant-from-0:
  assumes norm p ≥ 1
  shows between (0, p) (normalize p)
 ⟨proof⟩

lemma between-normalize-if-near-0:
  assumes norm p ≤ 1
  shows between (0, normalize p) p
 ⟨proof⟩
1.2.4 Lemmas on radiant-of

**lemma** radiant-of:

\[0 \leq \text{radiant-of } p \land \text{radiant-of } p < 2 \ast \pi \land \text{of-radiant } (\text{radiant-of } p) = \text{normalize } p\]

⟨proof⟩

**lemma** radiant-of-bounds [simp]:

\[0 \leq \text{radiant-of } p \text{ radiant-of } p < 2 \ast \pi\]

⟨proof⟩

**lemma** radiant-of-weak-ubound [simp]:

\[\text{radiant-of } p \leq 2 \ast \pi\]

⟨proof⟩

1.2.5 Main Equations for Transforming to Polar Form

**lemma** polar-form-eq:

\[\text{norm } p \ast R \text{ of-radiant } (\text{radiant-of } p) = p\]

⟨proof⟩

**lemma** relative-polar-form-eq:

\[Q + \text{dist } P Q \ast R \text{ of-radiant } (\text{radiant-of } (P - Q)) = P\]

⟨proof⟩

1.3 Ptolemy’s Theorem

**lemma** dist-circle-segment:

- **assumes** \(0 \leq \text{radius } \theta \leq \alpha \leq \beta \leq 2 \ast \pi\)
- **shows** \(\text{dist } (\text{center } + \text{radius } \ast R \text{ of-radiant } \alpha) \ast (\text{center } + \text{radius } \ast R \text{ of-radiant } \beta) = 2 \ast \text{radius } \ast \sin ((\beta - \alpha) / 2)\)

⟨proof⟩

**theorem** ptolemy-trigonometric:

- **fixes** \(\omega_1, \omega_2, \omega_3 :: \text{real}\)
- **shows** \(\sin (\omega_1 + \omega_2) \ast \sin (\omega_2 + \omega_3) = \sin \omega_1 \ast \sin \omega_3 + \sin \omega_2 \ast \sin (\omega_1 + \omega_2 + \omega_3)\)

⟨proof⟩

**theorem** ptolemy:

- **fixes** \(A, B, C, D \text{ center } :: \text{real } \sim 2\)
- **assumes** \(\text{dist center } A = \text{radius and dist center } B = \text{radius}\)
- **assumes** \(\text{dist center } C = \text{radius and dist center } D = \text{radius}\)
- **assumes** \(\text{ordering-of-points: }\)

  - \(\text{radiant-of } (A - \text{center}) \leq \text{radiant-of } (B - \text{center})\)
  - \(\text{radiant-of } (B - \text{center}) \leq \text{radiant-of } (C - \text{center})\)
  - \(\text{radiant-of } (C - \text{center}) \leq \text{radiant-of } (D - \text{center})\)

- **shows** \(\text{dist } A \ast \text{dist } B \ast \text{dist } B \ast \text{dist } D = \text{dist } A \ast \text{dist } C \ast \text{dist } D + \text{dist } A \ast \text{dist } B \ast \text{dist } C\)

⟨proof⟩
References

